COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COST Action HELEN

COST ACTION CA 20139

Holistic design of taller timber buildings (HELEN)

STATE OF THE ART REPORT

1. December 2022

COST Association AISBL
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Foreword

The COST Action CA 20139, Holistic design of taller timber buildings (or HELEN as we like to call it) has set its scope and goals rather different compared to previous COST Actions in the field of the built environment. Opposed to focusing on more specific problems, we have cast the net very wide; as wide as we could. The reason behind is quite simple. Buildings are complex, interdisciplinary systems that only function well when all their subsystems, all their bits and bobs function well too. Individually, but very importantly, also in interaction among themselves. All buildings are complex systems, however, taller multistorey timber buildings are even more complex than their concrete, steel, or masonry counterparts. Timber is a beautiful and renewable material that can last for centuries in a building if designed and executed correctly. But it is also a bit of a capricious material that does not forgive mistakes that easily. Hence, we need to design it well, with all the demands a building needs to fulfill dealt with in parallel and not individually. This COST Action goes beyond the design codes which for the most part only focus on individual design fields or specifics. It brings together a spectrum of engineering fields that are involved in a building's design, along with the architects and builders. The Action also strives to bring investors, municipalities, and policy makers on board. Through an interdisciplinary debate, the potential issues multistorey buildings may face can be identified quicker, easier, and more importantly before they occur in practice. The practice has already come a long way, however with the European as well as global efforts to increase timber construction, we will be running into new challenges – this Action strives to be one step ahead of these challenges. The state-of-the-art report is the first important step in the process. This four-part report, nearly 400 pages long, gives an overview of a wide range of topics contemporary multistorey timber buildings face (or will face soon). The first part deals with design for robustness, adaptability, disassembly, reuse, and repairability; the second part with deformations and vibrations; the third part with accidental loads; and the fourth with sustainability and durability. This state of the art forms a base for further discussions within the interdisciplinary group of 280 people (at the time of this publication) and growing. Data will be further supported by interdisciplinary interactive surveys, workshops and training schools, and short-term scientific missions planned in the next three years. We are confident that at the end of 2025 when the Action finishes, we will be providing the timber construction industry, building investors and users with guidelines that will enable safer, more robust, and more comfortable multistorey timber buildings with optimal raw material use.

Iztok Šušteršič, CA chair

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COST Action CA 20139
Holistic design of taller timber buildings (HELEN)

Design for robustness, adaptability, disassembly and reuse, and repairability of taller timber buildings: a state of the art report

Edited by

Pedro Palma and Gerhard Fink (list of authors in pages 3-4)

Funded by the European Union

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

General info

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The sole responsibility of the content of the various contributions lies with their authors.

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Impressum

Design for robustness, adaptability, disassembly and reuse, and repairability of taller timber buidlings: a state of the art report.ban

COST Action CA20139 – Holistic Design of Taller Timber Buildings (HELEN).

Working Group (WG) 1 – Design for robustness, adaptability, disassembly and reuse, and repairability.

WG 1 and its subgroups (SGs) are coordinated by Pedro Palma, Maria Felicita, Kristina Kröll, Lisa-Mareike Ottenhaus, Felipe Riola-Parada, Gerhard Fink, José Manuel Cabrero, Reinhard Brandner, and Robert Jockwer.

December 2022

Foreword

Working Group (WG) 1 of COST Action CA 20139 HELEN deals with aspects related to design for **robustness**, **adaptability**, **disassembly and reuse**, and **repairability** in taller timber buildings.

As of October 2022, WG 1 has 102 registered members from 40 different countries. About 80% of the members are also members of other WGs, 35% of which are also members of WG 4 and 25% are members of all other WGs. This shows the broad scope and interdisciplinary nature of the topics addressed in WG 1.

After the 1st WG 1 meeting[1] in Izola (SI), on 24-25.05.2022, WG 1 was organised into one Sub-Group (SG) on robustness and disproportionate damages:

- SG Robustness, coordinated by Pedro Palma (Empa, Switzerland) and Maria Felicita (TU Delft, The Netherlands)

and three subgroups (SG) related to the circular economy:

- SG Adaptability, coordinated by Kristina Kröll (University of Wuppertal, Germany), Lisa-Mareike Ottenhaus (The University of Queensland, Australia), and Felipe Riola-Parada (City University of Applied Sciences Bremen, Germany);
- SG Design for disassembly and reuse, coordinated by Gerhard Fink (Aalto University, Finland) and José Manuel Cabrero (Navarra University, Spain);
- SG Repairability and maintenance, coordianted by Robert Jockwer (Chalmers University, Sweden).

The documents collated in this publication were written within the scope of the various SGs and were revised based on comments received during and after the 2nd CA 20139 Plenary Meeting[2] in Gothenburg (SE), on 04-05.10.2022.

The objective of these documents is to give an introduction to the topics of WG 1 and to motivate other members to identify possible collaborations and actively participate in the work of WG 1.

1 Draft minutes and presentations of the 1st WG 1 meeting, in Izola (SI), temporarily available online at https://polybox.ethz.ch/index.php/s/lOmpX9G8YJ89asb.

2 Draft minutes and presentations of the WG 1 Session during Gothenburg's Plenary Meeting temporarily available online at https://polybox.ethz.ch/index.php/s/zUUgZntlYw6jEsC.

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Contents

SG Robustness

This SG deals with the topics of resistance to disproportionate damages, including structural and non-structural robustness and resistance to progressive collapse. The documents in this section include a short introduction to robustness and related terminology, a description of the stakeholders and design framework for resistance to disproportionate collapse, and case studies of strategies against disproportionate collapse in modern taller timber buildings:

SG Adaptability

This SG deals with topics related to changes in the functional use of buildings, how the design of tall timber buildings can account for adaptability-related requirements (e.g. versatility, convertibility, expandability), and with the interactions between these and other requirements (e.g. robustness, durability). The documents in this section are:

SG Design for disassembly and reuse

This SG addresses the topics of design for disassembly and reusability in the context of tall timber buildings. This includes the design of new timber buildings taking into account future needs of disassembly and maximising reuse possibilities, but also the reuse of reclaimed materials in new buildings. The documents in this section are:

SG Repairability and maintenance

This SG deals with issues of maintenance of the building stock during its planned service life and of restoring the original conditions in case of damages. It aims at studying: i) maintenance strategies for tall timber buildings; ii) the design of new buildings taking into account eventual need for repairs; iii) repair strategies for tall timber buildings; and iv) how to hold the materials' grey energy within the building stock and prevent unnecessary consumption of new resources and energy. The documents in this section are:

Horizontal topics

These contributions cover topics that intersect and are of interest for several SGs. The documents in this section are:

SG Robustness

Robustness – Introduction and terminology

Pedro Palma, Empa – Materials Science and Technology (Switzerland);
Maria Felicita, Delft University of Technology (The Netherlands)

1 Robustness and disproportionate consequences

The term *robustness* is often used to describe the ability of a building to accommodate some kind of *initial local damage* without it propagating and causing *disproportionate* consequences. Robustness therefore assumes that a hazardous event has occurred and that the building was locally affected by it (Figure 1) and is, therefore, one aspect of the resistance to disproportional consequences.

When the triggering hazardous event (e.g. malicious or unintentional actions, fire, decay, overloading) can be reliably known in advance, specific measures can be adopted. However, it is often the case that the initial local damage is caused by unforeseen or even unforeseeable events that cannot be explicitly accounted for in the design and use of the building. This makes *robustness* a prominent aspect in avoiding consequences that are *disproportionate* to the original hazardous event or damage. The disproportionality of the consequences can only be assessed in relation to predefined requirements or expectations (e.g. area that is allowed to collapse in case a load-carrying column is severely damaged, construction elements that are expected to be replaced after a fire in a compartment). However, specifying these requirements is not actually an engineering problem and can even be more challenging (Starossek 2018), since it must reflect the will of the owner, the concerns of other stakeholders that might be affected by the potential disproportionate consequences (e.g. civil authorities, insurance companies, neighbours), and even public opinion. Therefore, agreeing on acceptable direct and indirect consequences might require administrative or even political decisions.

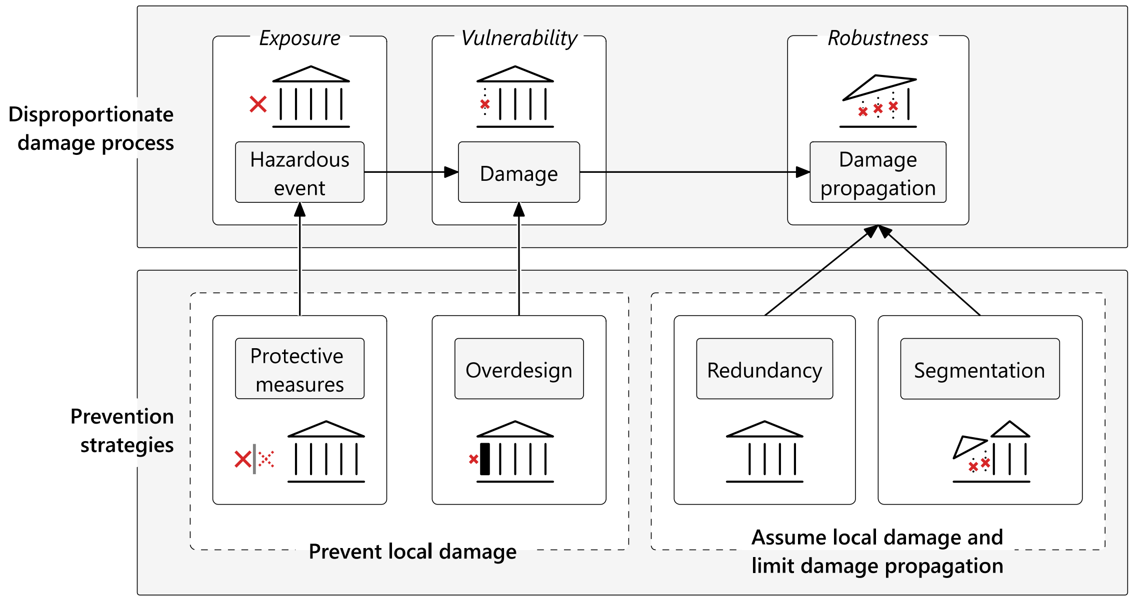

Figure 1: Disproportionate damage process and corresponding prevention strategies, based on Starossek and Haberland (2010), Palma et al. (2019), and Mpidi Bita et al. (2022)

2 Design strategies

Design strategies against disproportionate consequences commonly fall into one of the following categories (Figure 1).

1) *Prevent local damage:*
    a) *protection measures* aimed at reducing the probability of occurrence of the hazardous event (e.g. barriers against vehicle impact, active fire protection systems, water and damp proofing);
    b) *overdesign measures* aimed that reducing the vulnerability of *key elements* of the building, in case a hazardous event happens (e.g. overdesign load-carrying columns to withstand vehicle impacts, use materials less prone to deterioration, use effective firestops).
2) Assume initial local damage and *limit damage propagation:*
    c) *robustness measures* aimed at limiting damage propagation through:
        i) *redundancy* (e.g. design beams to carry vertical loads through catenary action in case a supporting load-carrying column is damaged, therefore creating an alternative load path); and/or
        ii) *segmentation* (e.g. design a fire compartment for full burnout, thus isolating it from its surroundings).
3) *Prescriptive rules*.

The effectiveness of i) *protection* or ii) *overdesign* strategies depends on how reliably the hazardous events can be foreseen and characterised. Since these are usually events with a very low-probability of occurring, the effectiveness of such measures can be very difficult to assess and to ensure for larger or complex buildings.

Strategies based on verifying or increasing iii) *robustness* require the definition of initial local damages and, therefore, also requires the identification of *key elements*, whose failure would result in unacceptable consequences. The design is then made assuming that these components are damaged. *Redundancy* strategies are based on providing alternative ways to fulfil the performance requirements by bypassing the damaged component. *Segmentation* strategies are based on isolating the damaged areas, either through weak fuse elements (e.g control joints) or strong isolating elements (e.g. fire walls between adjacent buildings).

The application of prescriptive design rules should be limited to buildings of minor importance, since their effectiveness is often unclear.

3 Quantifying robustness

Robustness is better achieved when considered from the early stages of conceptual design. Nevertheless, quantitative measures of robustness can be useful in some situations, such as when verifying explicit requirements or optimising the design (e.g. to assess the cost effectiveness of different strategies).

Quantitative measures of robustness are mostly based on comparing some measure of the damaged and undamaged systems or on assessing the response of the system to some initial damage (André and Faber 2019). Since different types of buildings are prone to different types of damages and damage propagation, there is no single "best" quantification of robustness (e.g. energy-based measures of structural robustness are better suited to assess impact-type progressive collapses, such as pancake-type collapses, whereas measures based on reserve load-carrying capacity are often suitable to assess redistribution-type progressive collapses and alternative load paths) (Starossek 2018). In any case, the crucial aspects of a robustness assessment are (Maes et al. 2006) a clear definition of the system being assessed, the identification of specific performance requirements; the identification of specific hazards, and the analysis of the consequences of damage within the system.

In the case of structural robustness, various quantification methods have been proposed, mostly through deterministic, reliability, and risk-based robustness indexes (Sørensen 2011; Chen Yong-Liang et al. 2016). These indexes, however, are not easily determined (except maybe for deterministic-based indexes) and, as all single-value indexes that summarise complex systems, only reveal the susceptibility of the structure to disproportionate collapse to some extent. In addition, they are also mostly not applicable in ordinary design practice. Target reference values for robustness indexes (e.g. like the target values for the reliability index β provided in prEN 1990:2021) against which the calculated indexes could be compared are also not available, making the indexes only useful for comparisons between not very dissimilar alternatives (i.e. same structure but different initial damage or different connectivity between elements) (Palma et al. 2019).

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Robustness – Importance for design of tall timber buildings

Maria Felicita, Delft University of Technology (The Netherlands)
Pedro Palma, Empa – Materials Science and Technology (Switzerland)

1 Structural robustness

The main goal of structural robustness is to prevent disproportionate collapse caused by errors in design and construction, lack of maintenance, and unforeseeable events (Kirkegaard et al. 2010). Structural robustness is a requirement in most major design building codes in the world, such as Eurocodes (prEN 1990:2021); however, detailed implementation guidance is not common. Existing design guidelines that address the prevention of disproportionate collapse through structural robustness are based on research and practical experience from traditional construction materials such as steel and concrete (Mpidi Bita et al. 2022). The most common methods for incorporating structural robustness into the design of a building are design for redundancy through alternative load paths (ALPs) and overdesign of key elements. ALP methods rely on the redistribution of loads across the structure, where the structural elements and connections must be designed to maintain their strength through large deformations and load reversals, and allow controlled load redistribution during local collapse (Ellingwood et al. 2007).

2 Robustness of tall timber buildings

The increasing popularity of engineered wood products has led to the development of larger, taller, and more complex timber structures than ever before. Moreover, European Union policies on transitioning to a bio-based circular economy has made the structural timber industry grow at an unprecedented pace, with the world's tallest timber building title having been broken many times since the mid 2010s ("List of tallest wooden buildings" 2022; Voulpiotis et al. 2021). The novelty and accelerated growth of these structures has led to uncertainties in terms of structural robustness, such as the susceptibility of such structures to disproportionate collapse and their ability to redistribute loads through ductile mechanisms within the structural members and connections.

The following characteristics of timber increase the potential of unexpected risks when scaling up to new heights:

- Brittle failure modes in timber members: Timber members fail mostly in a brittle manner, which makes timber connections a critical component in load redistribution.
- Low weight: Timber used in construction is approximately 5 times less dense than reinforced concrete and 15 times less dense than structural steel. The direct advantage of lighter building has a pitfall of being much more sensitive to horizontal actions (e.g. wind) and vibrations as the height of the building increases.
- Low connection stiffness: The often limited stiffness of most common timber connections becomes critical in taller buildings, namely for horizontal loads.
- Durability: The cumulative decay of wood by fungi and the migration of wood-boring beetles and termites due to warmer winters is a significant risk for taller buildings, in which repairs might be more complicated.
- Moisture-dependency: Timber is a naturally grown, hygroscopic material, with strength and stiffness negatively influenced by increased moisture.

- Combustibility: Large timber cross sections have some inherent fire resistance, but also contribute to the fire load and external charring and pyrolysis inside the cross sections can continue even after the cooling phase of a fire.
- Time effects: Timber creeps with time, even more so under wet conditions and wet-dry cycles, which can be critical on heavily loaded structures like tall timber buildings.
- Studies on the susceptibility of tall timber buildings to disproportionate collapse are limited (Mpidi Bita et al. 2022). Load redistributions within a structure in case of local failure is usually achieved through catenary/membrane action given that it allows the structure to maintain high load carrying capacities and deformations. However, such mechanisms required sufficient tensile capacity in the members, lateral stiffness, and strength of adjacent members, as well as rotational ductility of the connections, which is usually not implicit in timber structures. The brittleness of timber and the extreme importance of timber connections must be considered when designing for accommodating load redistributions within a structure, especially tall buildings.

For a brittle material such as timber, large deformations need to be accommodated through metal connectors to achieve ductility. Tests in novel connections have proven that timber assemblies can achieve the same mechanisms as reinforced concrete and steel buildings when sufficient ductility is provided (Mpidi Bita and Tannert 2019). However, this is not implied for standard metal connectors usually implemented in timber structures, for which the behaviour under high deformations and combined axial and bending loads is not well established. Design strategies based on overdesigning key elements seem to be popular, mostly because they are straightforward to design for, but do not directly contribute to increased capacity for load redistribution (Palma et al. 2019). The lack of reference projects, design guidance and requirements may impede the expansion of tall timber structures.

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Structural robustness – Stakeholders

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1 Importance of designing for resistance to disproportionate collapse

Given the relative novelty of taller timber buildings and the limited experience on their behaviour, resistance to disproportionate collapse should be considered by the stakeholders, also because of the symbolism of these structures and the media exposure that they tend to receive. Disproportionate collapse resistance is particularly relevant for tall timber buildings, given the current interest in their construction and ongoing "race" for the tallest timber building. The requirements set by civil and building authorities and insurance companies tend to reflect the current state of knowledge and experience, which are still limited, and the regulatory consequences of damages disproportionate to their inception in a tall timber building could be severe and long-lasting.

Decisions on robustness-related issues often require dealing with:

i) very-low probability and even unforeseeable hazardous events;
ii) planning mitigation strategies; and
iii) defining acceptable levels of damage.

The first two aspects can be particularly challenging, and are mostly engineering problems. The third aspect, however, is not something that can be decided by the structural design team alone and should be decided at the project stakeholder level. The definition of acceptable levels of total damage, i.e. the specification of performance requirements and the corresponding verification methods in case of an initial local damage can be even more challenging than the other aspects (Starossek 2018). It must reflect the will of the owner of the building, the concerns of all stakeholders, including the public who might be directly or indirectly affected by the damages. Therefore, it might require administrative or even political decisions (Starossek and Haberland 2010), hopefully supported by cost-benefit analyses for example.

2 Stakeholders

In scope of resistance to disproportionate collapse, stakeholders are not only the promoters and owners of the structure, but also those directly or indirectly affected by such a collapse, such as, e.g., users, civil and building authorities, the structural design team, insurance companies, the police, fire brigade, nearby hospitals, schools and other neighbours. Table 1 indicates roles and tasks in a typical tall timber building project.

The *promoters and owners* are naturally interested in optimising monetary costs of safety measures (e.g. fire safety and resistance to disproportionate collapse) and in reducing downtime in case of damages, namely downtime needed for repairs and the corresponding economic losses including associated reputational risk and losses. Promoters and owners often have no incentive to avoid externalising consequences (e.g. spill of hazardous materials into the environment after a collapse) and it is often up to the civil and building authorities to mitigate any consequences of such incidents.

Civil and building authorities must take the wider public interest into account and must be responsible for the specification of some performance objectives, in particular the acceptable levels of damage. The interests of an owner should obviously be taken into account, but it is the responsibility of the public authorities to ensure that the risk of a disproportionate collapse remains below/within acceptable levels. *Civil and building authorities* are often accused of being slow in allowing for new building technologies to be implemented at a large scale, but they have to consider many more aspects, including public opinion, in their decisions.

The *structural design team* is obviously interested in achieving a safe and economical design, preferably by following rational and well-established design frameworks, in which their responsibilities are clearly defined. If relevant, the structural designer must account for resistance to disproportionate collapse from the early stages of conceptual design and develop a design strategy (e.g. prevent local damage, limit damage propagation) and the corresponding verification procedures. This should take into account the owner's preferences and the requirements set by the authorities regarding acceptable levels of damage.

The design scenarios might represent exceptional situations (e.g. a sudden removal of a load-carrying element) and the design strategy might be based on non-standard load-carrying processes (e.g. catenary action, impact loading, very high deformations), well-established analysis and verification procedures might not be available or might be too conservative. Therefore, there can be a tendency to focus on simply overdesigning key structural elements, which might indirectly lead to some increase in robustness, but does not ensure nor prevent damage propagation. Therefore, civil and building authorities must be involved in approving the verification procedures envisaged by the design team, particularly for high-risk structures and even require independent design checks.

Amongst *insurance companies* there is a clear need for a better understanding of the performance of tall timber structures exposed to hazardous events (Giddings n.d.), namely fire, water damage, or other events that might trigger a disproportionate collapse. Following a well-defined design procedures and having more standardised, appropriate and relevant verification methods would surely increase the confidence to insure tall timber buildings.

Neighbours to a tall timber building are also a stakeholder. They are interested in short construction times, limited disruption, noise, and pollution, including possible increase in wind speed around a tall timber building. Timber buildings have significant competitive advantage in this regard, given the high degree of prefabrication and low weight, which often leads to faster and cleaner construction with relatively small teams. Timber buildings currently benefit from very good public opinion, but this can quickly change if they are perceived as unsafe, e.g. regarding fire hazards or disproportionate partial collapses, or if their lack of durability requires continuous repairs.

Table 1: RACI matrix (R = Responsible, A = Accountable, C = consulted, I = Informed).

Construction Phase	Promoter or owner	Consultant	Contractor	Other stakeholders
Feasibility stage / conceptual design	R	A	I	C
Option selection	A	R	C	I
Detailed design for single option	R	A	C	I
Independent project review	R	C	I	A
Construction	R	C	A	I
Verification	I	C	R	A
Post construction (maintenance, renewals)	A	C	R	I

3 Conclusions

The current popularity and positive sustainable impact of timber construction encourages the building of larger, taller, and more complex buildings. However, this incentive also puts these buildings in the public eye, which makes these buildings particularly susceptible to a strong pushback in case of their performance fails to meet the public's expectations, namely if they are perceived as unsafe or not durable. Given the relative novelty of tall timber buildings and the limited medium andlonger-term experience, stakeholders have the duty to keep the current positive public perception of timber buildings by adoptingcarefully devised teams, roles and tasks including a well-established design frameworks.

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Structural robustness – Design framework for resistance to disproportionate collapse

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1 Overview

The design framework for resistance to disproportionate collapse presented in his document (Figure 1) is based on the Starossek (2018) and comprise the following main parts:

i) risk assessment/classification of the structure;
ii) specification of hazard scenarios;
iii) specification of performance objectives;
iv) development of design strategies and corresponding verification procedures.

The level of *design requirements* should be based on the risk assessment of building and this can be achieved by undertaking the risk assessment and building classification frameworks described in Section 2. The specification of *hazardous scenario*s, such as threat-specific (e.g. impact of a car in a ground-floor column) or non-threat-specific events (e.g. notional damage such as a sudden removal of a structural component), and *performance objectives* (i.e. the acceptable level of damage/consequences) should involve other stakeholders besides the owner and the design team, namely the relevant civil and building authorities and an insurance company. For major projects, the specification of hazardous scenarios requires some experience, since the creation of general rules is difficult because of many possible scenarios and project-specific nature of many of them. Once the hazard scenarios are considered and the performance objectives are set, the structural design team then selects the *design strategies* (e.g. protection or overdesign measures to prevent local damage, robustness measures to limit damage propagation) and the *design verification procedures* (e.g. based on structural analysis models or even testing). A schematic overview of this design framework for resistance to disproportionate collapse is given in Figure 1.

For buildings with low importance and exposure it should be possible to achieve an adequate level of resistance to disproportionate collapse without any explicit design verifications, but increasingly complex verification are often required for buildings of high importance and/or exposure. For special structures, project-related criteria might even be required and this will involve not only the owner and the structural design team, but also stakeholders (e.g. civil and building authorities, insurance companies).

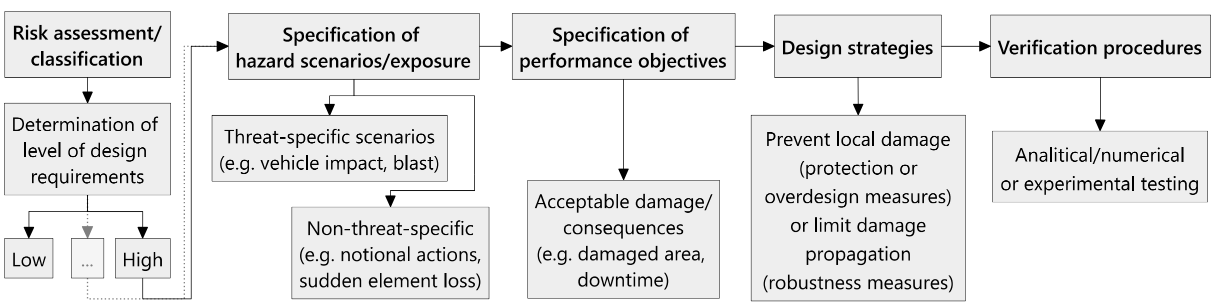

Figure 1: Design framework for resistance to disproportionate collapse, based on Starossek (2018).

2 Risk assessment and classification of buildings

The first step in defining robustness-related requirements is to assess the *importance* of the building, i.e. the *direct* and *indirect* risks or consequences of a collapse, and its *exposure*, i.e. the probability of occurrence of a hazardous event (e.g. accident, malicious or unintentional actions). In some cases, the *indirect* risks or consequences of a collapse (e.g. debris damaging infrastructure adjacent to the building, income losses due to halted activity, spread of hazardous materials, damage to public morale) can have a greater impact on the importance of the structure.

For these purpose of classification of buildings, the European structural design standard prEN 1990:2021 establishes five consequence classes, based on an indicative qualification of consequences (loss of human life or personal injury and economic, social or environmental consequences). The exposure of the structure, i.e. the level of threat, is not explicitly accounted for (or it is assumed proportional to the importance of the building). Different indicative design methods for enhancing the resistance to disproportionate collapse are given for the various consequences classes. The North American GSA (2013) establishes five facility security levels, based on the level of threat (i.e. the *exposure* of the structure) and the *importance* or significance (i.e. risks or consequences of collapse). These levels are assessed using evaluation factors that include criticality, symbolism (e.g. the US Capitol is assigned very high symbolism, whereas small offices in leased commercial buildings are assigned low symbolism), facility population, facility size and threat. Design requirements are then specified depending on the facility security level and number of storeys. The also North American UFC 4-023-03 for military buildings establishes four risk categories, defined based on the number of occupants, function of the building, and consequences of collapse. The *exposure* of the structure is, therefore, also not directly accounted for. Design requirements are specified for the different risk categories (Perhaps we should add the reference here too).

3 Specification of hazard scenarios / exposure

Hazardous events are abnormal actions that can occur during the construction and service life of the building. These are the design scenarios for which the performance objectives / level of damaged of the structure should be evaluated.

Threat-specific scenarios can be foreseen (e.g. impact of a vehicle, far-field blast) and the corresponding actions on the structure might even be reasonably well estimated. However, given that it is effectively impossible to identify and quantify all hazards, it is clear that the list of identified scenarios is incomplete and the corresponding actions have a significant uncertainty. Threat-specific scenarios are mostly project-specific (e.g. the probability and characteristics of the impact of a vehicle depends on the location and access to the building) and it is not always straightforward to prescribe general rules. These scenarios allow for design strategies against disproportionate collapse based on preventing local damage (protection measures to reduce the probability of occurrence of a hazardous event and overdesign measures to reduce the probability of damage in case of a hazardous event). The specification of threat-specific scenarios should be complemented with threat-independent scenarios.

Threat-independent scenarios assume an initial notional damage or action (e.g. sudden removal of a load-carrying member), independently of a specific triggering event. These scenarios assume that damage has occurred and the design strategies against disproportionate collapse must be focused on limiting damage propagation (robustness-related measures), namely redundancy and/or segmentation.

4 Specification of performance objectives / acceptable level of damage

The performance objectives or acceptable level of damage must reflect the promoter's or owner's brief and requirements, but also the concerns of other stakeholders, who might be affected by a disproportionate collapse (e.g. civil and building authorities, insurance companies, neighbours). In some cases, agreeing acceptable *direct damages* (e.g. collapsed area) will mostly involve the owner and the insurance company, but depending on the use of the building, civil and building authorities might also impose limitations on the acceptable level of damage (e.g. the acceptable collapsed area will be different for a retail building than for a remote and mostly unoccupied storage warehouse).

Indirect damages are not directly related to the material damage of the collapse, but arise from the impact of the collapse in the interests or economical activities of stakeholders (e.g. downtime in manufacturing during structural repairs, obstruction of public roads, damage of public infrastructure) and even in the public opinion. Therefore, specification of acceptable levels of indirect damages is made by civil and building authorities, who have the duty to protect public interest. The assessment of indirect damages in terms of costs is not always straight forward (e.g. spread of a hazardous material to the environment) and so it is not always straightforward to sum direct and indirect damages.

5 Specification of design strategies

Resistance to disproportionate collapse can be achieved at different levels.

- Preventing local failures by
    - adopting protective measures (to reduce the probability, extent or mitigate the exposure of the structure to abnormal events), or by
    - overdesigning key elements (to reduce the probability of damage in case of a hazardous event, i.e. reduce the vulnerability of key elements and increase safety against initial failure).
- Assuming local failure and limiting damage propagation (robustness-related measures to increase insensitivity to initial damage), through
    - redundancy (e.g. design beams to carry vertical loads through catenary action in case a supporting load-carrying column is damaged, therefore creating an alternative load path); and/or
    - segmentation (e.g. design a fire compartment for full burnout, thus isolating it from its surroundings).

Design strategies based on adopting *protective measures* often fall outside the scope of structural design (e.g. vehicle barriers, access control, active fire protection). Strategies based on *overdesigning key elements* should be a last resort (Arup 2011; Hewson 2016; Huber et al. 2018), used only in cases where other alternatives are not viable or too costly. Design of key elements follows the common design procedure, even if the considered actions are anything but common, and the corresponding structural design can often be done in accordance with available guidance (Palma et al. 2019).

The *redundancy* strategy is based on providing an alternative load path (ALP) for the forces not transmitted anymore through failed components. It is based on assessing the behaviour of the remaining structure after an initial notional damage. A commonly assumed initial damage is the notional removal of one (or several) components of the structure and a so-called *element-removal analysis* is then performed, with the objective of evaluating if the remaining structure is able to accommodate the damage. Redundancy on its own might not be suitable to avoid disproportionate collapse. In the case of repetitive structures, systematic design or execution errors can compromise the ability of a structure to redistribute loads and lead to progressive collapse (Munch-Andersen and Dietsch 2011), as the alternative load paths are all affected by a common-cause failure.

In these cases, *segmentation* can be an adequate design strategy. The objective of this strategy is to compartmentalise the structure in a way that collapse progression after an initial damage is halted at predefined locations, either through fuse-type elements or by having control joints at which the segments are physically separated. Most common solutions for *vertical segmentation* rely on providing shock-absorbing zones with high energy dissipation capacity. Examples of vertical segmentation are scarce, however, the 14-storey timber building "Treet", in Norway, includes a paradigmatic example (Abrahamsen and Malo 2014): this building has two "power storeys" that carry a prefabricated concrete slab on top of which four levels of residential modules are stacked; these "power storeys" should be able to halt a progressive collapse of the stacked residential modules, limiting the extent of collapse.

6 Verification procedures

The verification procedures should allow evaluating that adopted design strategies specified performance objectives / acceptable levels of damage are met for the various hazard scenarios. The verification procedures usually comprise analytical or numerical models of the structure that are able to adequately capture the most relevant phenomena. Simplified analyses can be based on linear quasi-static structural models with dynamic amplification factors (Mpidi Bita and Tannert 2022) or nonlinear quasi-static (pushover) analyses (Huber et al. 2020, 2021), but more advanced non-linear dynamic analyses are also possible (Mpidi Bita and Tannert 2019; Cao et al. 2021). The main issue with the modelling of timber buildings under these scenarios is the current lack of experimental validation. Therefore, experimental testing should be required for high-risk buildings. In any case, verification procedures should be approved by the civil and building authorities and/or independent external entity. The verification procedure should be a check of all relevant project-specific designs as well as correct construction and installation.

7 Conclusions

Resistance against disproportionate collapse has to be seen in a broader design framework, which comprises the risk assessment/classification of the structure, followed by the corresponding specification of relevant exposures, design strategies, and verification procedures. Resistance against disproportionate collapse is not at all limited to the use of more or less advanced structural analysis techniques, which is the impression that is often given, and, when required, has to be taken into account from the initial stages of conceptual design.

The current popularity of timber construction encourages the construction of larger, taller, and more complex buildings. However, this incentive also puts these buildings in the public eye, which makes them particularly susceptible to a strong pushback in case their performance fails to meet the public's expectations, namely if they are perceived as unsafe or not durable. Given the relative novelty of tall timber buildings and the limited medium- long-term experience, stakeholders have the duty to keep the current positive public perception of timber buildings by adopting carefully devised design procedures based on well-established design frameworks has the one presented above.

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Structural robustness – Case studies of strategies against disproportionate collapse in multi-storey timber buildings

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Maria Felicita, Delft University of Technology (The Netherlands)

Foreword

The case studies presented in this document are mostly based on the publication "Prevention of Disproportionate Collapse for Multistory Mass Timber Buildings: Review of Current Practices and Recent Research", by Mpidi Bita et al. (2022).

1 Case studies

1.1 Stadthaus apartment building

The Stadthaus is a nine-storey apartment building in London, UK, that was completed in 2009 (Wells 2011). It is a platform-type construction with cross laminated timber (CLT) floor panels on CLT walls. The design strategy against disproportionate collapse was based on the alternative load path (ALP) approach in EN 1991-7:2006. The load-carrying walls are laid out in both directions and have small tributary loading areas. The floor panels were designed to act as cantilevers or span in two directions above damaged zones and the walls to act as deep beams.

1.2 Treet building

The fourteen-story Treet building in Bergen, Norway, was built in 2015 and was the tallest timber truss construction in the world. The structure consist of massive vertical glued laminated timber (GLT) trusses and intermediate concrete storeys, on which prefabricated apartment modules are stacked. Analyses were performed to check that main structural members and connections can undergo large deformations in case a members of the main trusses is damaged. The concrete storeys were designed to withstand failures in the prefabricated modules and the design of other secondary members also accounted for debris loading (Abrahamsen and Malo 2014; Malo et al. 2016).

1.3 Redstone Arsenal hotel

The four-story Redstone Arsenal hotel in Huntsville, USA, was constructed in 2016. CLT panels were used all internal and exterior walls, floors, and roof. Like the Stadthaus, the highly redundant layout of the CLT walls provides some redundancy for load redistribution. The structure was designed for the force and deformation demands obtained from a linear-elastic element-removal analysis in accordance with GSA (2013) and UFC 4-023-03 guidelines (Steimle 2016).

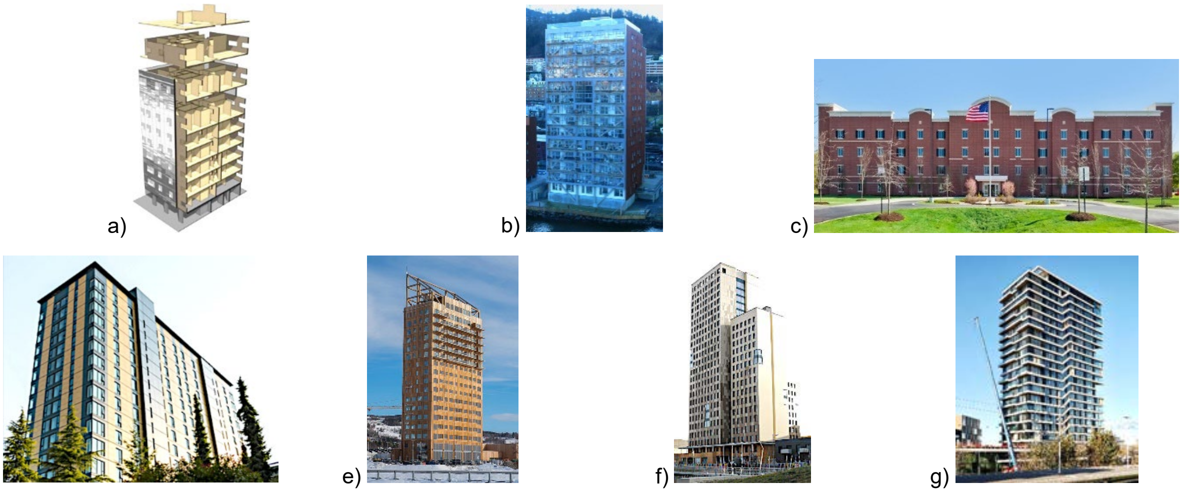

Figure 1: Case studies: a) Stadthaus apartment building; b) Treet; c) Redstone Arsenal hotel; d) Brock Commons; e) Mjøstårnet; f) HoHo: g) HAUT.

Sources: a) https://commons.wikimedia.org/wiki/File:Murray_Grove_Cross-Section.jpeg; b) https://commons.wikimedia.org/wiki/File:Treet_(Bergen)_011.jpg; c) https://digital.ihg.com/is/image/ihg/candlewood-suites---military-huntsville-4439365680-2x1; d) https://www.flickr.com/photos/ubcpublicaffairs/36357661945; e) https://commons.wikimedia.org/wiki/File:Mj%C3%B8st%C3%A5rnet.jpg; f) https://commons.wikimedia.org/wiki/File:HoHo_Wien_Vienna_19-20_IMG_2225.jpg; g) https://commons.wikimedia.org/wiki/File:HAUT_Amsterdam2.jpg.

1.4 Brock Commons building

The Brock Commons is an eighteen-storey building in Vancouver, Canada, and was the tallest timber building when completed in 2017. The structural system comprises a concrete core and CLT floor panels point-supported on timber columns (Poirier et al. 2021). Design followed the element removal approach of EN 1991-1-7. The multi-span CLT floor panels were designed for two-way action and cantilevering in the case of loss of a column and the column-to-column connections were design to carry tension forces and hold the floor below (Fast and Jackson 2017).

1.5 Mjøstårnet building

The Mjøstårnet is an 18-storey building in Brumunddal, Norway, and was the tallest timber building at its completion in 2019. The structure comprises a GLT framed truss and CLT floors. Concrete floors were used in the upper storeys to reduce wind-induced vibrations. The columns were overdesigned to resist a pressure of 34 kPa, based on EN 1991-1-7:2006. The connections between the GLT elements were designed to exhibit a ductile failure mode and the structure was designed to withstand the impact of a falling concrete floor (Huber et al. 2018).

1.6 HoHo Wien

The HoHo Wien is a 24-storey hybrid concrete-timber building in Vienna, Austria. As in the Brock Commons building, the column-to-column connections were design to carry tension forces and hold the floor below in case of column loss. Horizontal and vertical ties were used to provide alternative load paths: the vertical ties consisted of glued-in steel rods connected to the concrete beams; the horizontal ties consisted of on-site casted reinforcement bars between concrete beams and floors (Woschitz and Zotter 2017).

1.7 HAUT

The HAUT is a 21-storey hybrid concrete-timber building in Amsterdam, Netherlands. The lateral stability is provided by a concrete core and two CLT shear walls. The transfer of the vertical loads is given by load bearing CLT walls, which support TCC floors spanning in one direction. Wherever the floor edges are not supported by a load bearing wall, glulam down stand beams are introduced. These beams double as a tension ring around the perimeter of the floor acting as a structural tie (Verhaegh et al. 2020).

2 Conclusions

The examples above show that various design approaches against disproportionate collapse have been used in different types of multi-storey timber buildings. Robustness-related aspects were explicitly considered from the early conceptual design process and formed the adopted structural solutions and detailing. The design strategies against disproportionate collapse included: providing ALPs based on floor panels acting as cantilevers, spanning in two directions, and walls above removed elements acting as a deep beams; designing columns to carry tension forces and hold the floors below; designing ductile connections; and vertically segmenting the building using strong floors.

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SG Adaptability

Adaptability – Introduction and terminology

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1 Definition of adaptability

Adaptability can be defined as a built-in ability of buildings to adapt to change by accommodating different uses, different spatial and functional configurations without significantly affecting the building, ongoing activities or the environment (Kronenburg, 2007). On this basis, adaptability plays an important role in improving the sustainable performance of a building. The ability to withstand the test of time as the spaces and components of the building continue to change opens up many possibilities, including each pillar of sustainable development (Nakib, 2009)

The so-called great acceleration (Steffen et al. 2015) of current socio-economic processes, mainly driven by the continuous growth of the world population and consumption, has relevant effects on the functional requirements for the changeability of buildings. Innovative technical solutions and new spatial structures are needed to be investigated seeking for the highest degree of interaction, flexibility and adaptability enabling sustainable adjustments of architectural forms according to socio-cultural and climate needs over time. In this context, the consideration of the life cycle of a building is not only reduced to its conception and realisation, but extends to the type and duration of its use. The temporal component is therefore considered an indispensable parameter of the architectural process, in which the concepts of "adaptability" and "flexibility" play a major role. Both concepts have often and erroneously been used as synonyms. However, adaptability refers to use-neutral spaces that can be adapted to different social purposes without changing their physical form. Flexibility defines the fitting capacity of a building through easy and uncomplicated physical changes, what means that the building concept should allow for an eventual ability to change by connecting, dividing, enlarging and merging spaces without great effort (Groák, 1992). The hypothesis of this paper is that adaptable buildings result from an interaction between space, construction and use and formulate the following questions:

- Which spatial structures and constructions allow for the highest degree of interaction, flexibility and adaptability?
- How many different levels of flexibility and adaptability can be defined in a building and which are their requirements?
- How adaptable and flexible structures affect other parameters? Which conflicts must be considered? How can those be solved?

2 Types of adaptability

To make a building adaptable, the questions are: what changes can occur & how can they be managed? Brand defines six shearing layers of change, which are site, structure, skin, services, space plan and stuff for describing the expected life cycle of building components (Brand, 1995). Later, the book "Adaptable Architecture" (2016) by Schmidt and Austin describes six different types of adaptability. The purpose of these types is to illustrate the kind of adaptability that is desired. The typification thereby addresses the question: What types of adaptability can occur? How can these be taken into account?

In the following, these types are summed up to give an overview of the possible changes in a building:

- **Adjustable – change of task/user**: e.g. furniture, furnishings, appliances
- **Versatile – change of space**: e.g. the layout of the rooms
- **Refitable – change of performance**: e.g. change in the performance of a building due to a change in the space, services or building envelope
- **Convertible – change of use**: e.g. change in the performance of a building due to a change in the space, services or building envelope
- **Scalable – change of size**: e.g. enabling horizontal and vertical extension
- **Movable – change of location**: e.g. by enabling easy assembly and disassembly, more suitable for temporary structures (Schmidt and Austin, 2016)

With regard to the planning of a multi-storey timber building, as envisaged by this COST Action, the adaptability types "Versatile", "Refitable", "Convertible", "Scalable" are particularly important. Against this background, the next chapter will classify multi-storey timber buildings into categories of adaptability.

3 Case studies

The following projects have been selected to be analysed in regard to their adaptability type and the solutions implemented.

- Oxley Woods (UK 2008) Rogers Stirk Harbour and Partners
- Z8 (Germany 2018) ASUNA / Hüls Engineers
- Walden 48 (Germany 2020) Scharabi + Raupach / IFB
- Collegium Academicum IBA (Germany 2022) DGJ Architektur / Pirmin Jung
- Illwerke Zentrum Montafon, IZM (Austria 2013) Hermann Kaufmann Architects / Merz Kley Partner

Table 1: Summary of Case Study Projects

Project	Adaptability type	Implemented system	Outcome
Oxley Woods	Adjustable, Refitable, Scalable	Timber frame and panels	Different combination of rooms Adding additional storey with add-on pieces Change of perfomance
Z8	Versatile, Convertible	Post and beam	Combination of use Different flats configurations
Walden 48	Adjustable, Refitable, Versatile	Cross-wall load-bearing CLT walls with long-span slabs	Open living space Different housing units
Collegium Academicum IBA	Versatile	Non load-bearing inner walls with a modular approach and detachable timber-timber joints	Flexible use of apartments Adaptability over time
ZM - Illwerke Zentrum Montafon	Convertible, Adjustabl	Timber-concrete rib decks on a central steel beam	Big spans in the central axis and thickness reduction

4 Conflicts and Design Strategies

4.1 Conflicts

- **Conflicts (01)**: in the case of adaptable spaces and flexible buildings, many times the strategy for allowing different uses (or allowing a change of configuration without changing use, like changing the configuration of housing units) leads to the use of structural systems with **medium/big spans**, with the objective of creating bigger spaces free of load-bearing elements (study cases: Walden 48, IZM). These structures are more demanding and costlier and therefore they originate bigger initial investments. An advantageous cost-balance can be achieved only taking into account the whole life-cycle of the building and the potential of savings in the future cases of uncomplicated physical changes.
- **Conflicts (02)**: design for flexibility assumes that “future cases of uncomplicated physical changes” should be expected. In order to achieve this, the conceptual design of connections takes a relevant role and the use of **reversible joints** appears as desirable. This adds a task to be performed by the connections themselves: they do not only have to perform properly after being installed, they also have to allow elements being removed and connected again, and this ideally for several cycles until the final recovery. This extra performance and robustness can add complexity and cost to the joints.
- **Conflicts (03)**: design for flexibility can conflict with the run of **building installations** as usual, where building installations have to be integrated for a particular final solution. The possible “future cases of uncomplicated physical changes” have to be anticipated and planned for allowing them from the very beginning.

4.2 Design strategies

- **Design strategies (01) - Hybridization**: the use of timber **hybrid structures** appears as a common strategy in order to achieve the goals and propose solutions to the conflicts stated in the previous point. Timber-concrete decks (*study cases:*

Walden 48, IZM) or the combination of timber structures with steel elements (*study cases: IZM*) can be used for achieving bigger free spans

- **Design strategies (02) - Detachable Joints**: the use of robust **detachable joints** able to withstand several cycles of assembly and disassembly appears as desirable. Properly designed steel connectors can fulfil this function and in the case of timber-timber connection the use of stronger hardwoods at these points appears as an alternative (*study cases: Collegium Academicum IBA*) (Drexler, 2021)
- **Design strategies (03) - Building Services**: a modular and combinatorial spatial approach can be used for defining the possible run of building services. A clear definition of **installation cores and main shafts** is necessary for serving and defining the differents combination of spaces anticipated in the design (*study cases: Collegium Academicum IBA*)

Links for the Case Studies:

Project	Link
Oxley Woods	http://www.oxleywoods.com/
Z8	https://www.asuna-leipzig.de/zz8
Walden 48	http://www.anneraupach.com/portfolio-items/walden-48/ https://scharabi.de/walden-48/
Collegium Academicum IBA	https://dgj.eu/portfolio/dgj223-iba-collegium-academicum/
ZM - Illwerke Zentrum Montafon	https://www.hkarchitekten.at/de/projekt/izm-illwerke-zentrum-montafon/

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Working definitions of ‘adaptability’ and ‘flexibility’ for use in research on buildings designed for change

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1 Introduction

This paper introduces a working definition for flexibility and adaptability in housing design, that has been developed from a state-of-the-art literature review of Design for Adaptability for research with a focus on the design of timber buildings. The themes of flexibility, adaptability, and principles of Circular Design that underpin the research are relevant for adaptable building design of taller buildings and designing adaptable buildings in urban and suburban contexts.

For this paper, it is understood that building construction internationally needs to transition from the linear ‘take-make-model’ to the alternative Circular Economy (CE) (Ellen Macarthur Foundation, 2015). Literature about designing buildings towards a CE has expanded significantly in the last few years (Munaro et al., 2020) and Design for Adaptability (DfA) has become a growing area of research (Askar et al., 2022; Askar et al., 2021; Aziz et al., 2020; Geldermans et al., 2019; Geldermans, 2016). This paper will refer to building design for a CE as it is otherwise known as Circular Design (CD) (Baker-Brown, 2017; Cheshire, 2016).

2 Definitions for Flexibility and Adaptability

In the CD literature a key approach to increasing building longevity is to design buildings that are flexible and adaptable to the changing needs of their occupants and contexts (ARUP and Ellen Macarthur Foundation, 2020; Cheshire, 2016; Cimen, 2021; Manohar, 2017). Yet in the literature, both terms ‘flexible’ and ‘adaptable’ buildings, are used and sometimes interchanged in meaning (Askar et al., 2021). To clarify the difference between the two adjectives, their use in the English language can be referred to. The *Oxford English Dictionary* (OED, 2021) has meanings of the adjective ‘flexible’ that can be applied to buildings:

> Flexible, *adj. n*. 1.a. *adj.* Capable of being bent, admitting of change in figure without breaking; yielding to pressure, pliable, pliant. 3.a. That can be ‘bent’, inclined, or rendered favourable to. 4.a. Susceptible of modification or adaptation to various purposes or uses; pliant, supple.

Using these meanings literally, a flexible building allows changes of use to occur by the building having the capacity to allow change without ‘breaking’, or parts of the building can be easily modified or ‘bent’, such as an interior with movable screens.

Likewise, referring to dictionary meanings of the adjective ‘adaptable’ applied to buildings:

> Adaptable, *adj.* ‘1. Capable of being applied or used in different conditions or contexts: capable of being modified or amended, especially so as to be put to a new use or serve a new purpose. 2. Able to adjust to new conditions or situations, or to change in one’s environment. (OED, 2021)

When these capabilities are used to describe an adaptable building, changes to the physical fabric of the building are usually required. For a building to facilitate new functions different to the functions which it was originally designed for, the building undergoes a process of change. To enable buildings to adapt to change without damaging the materials that they are constructed from, they need to be designed for future change (Friedman, 1997; Kronenburg, 2007; Schmidt & Austin, 2016; Schneider & Till, 2007a).

One important theory that enables change in buildings, is Brand's concept of a building as 'shearing layers of change'; with the inner layers acknowledged as having shorter lifespans to enable change or replacement without affecting the integrity of the outer layers (Brand, 1995). In this paper, Brand's layers of change are used to define parts of the building that change in either adaptable or flexible buildings, as noted in Fig.1 below.

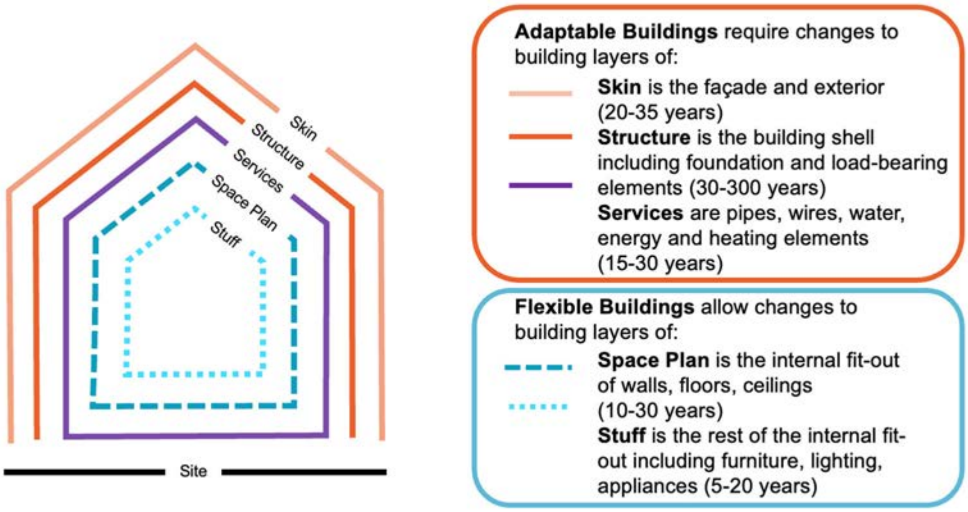

Figure 1 Brand's Shearing Layers of Change with Flexible and Adaptable Building Layers

Another important work in the DfA literature is Schmidt and Austin's (2016) comprehensive theory for adaptable buildings; through analysis of 290 buildings designed for change they defined six levels of adaptability, in order of increasing change to the building: adjustable, versatile, refitable, convertible, scalable and movable (Fig. 2) (Schmidt & Austin, 2016). Levels of 'adjustable' and 'versatile' usually occur within the building interior and can be modified by occupants themselves with little change to the building; in this research these levels are regarded as 'flexible' buildings. The adaptability levels of 'refitable' - to change the services, 'scalable' - to change the size of the building, 'convertible' - to change the use and 'movable' – change of location, are regarded as truly 'adaptable' buildings.

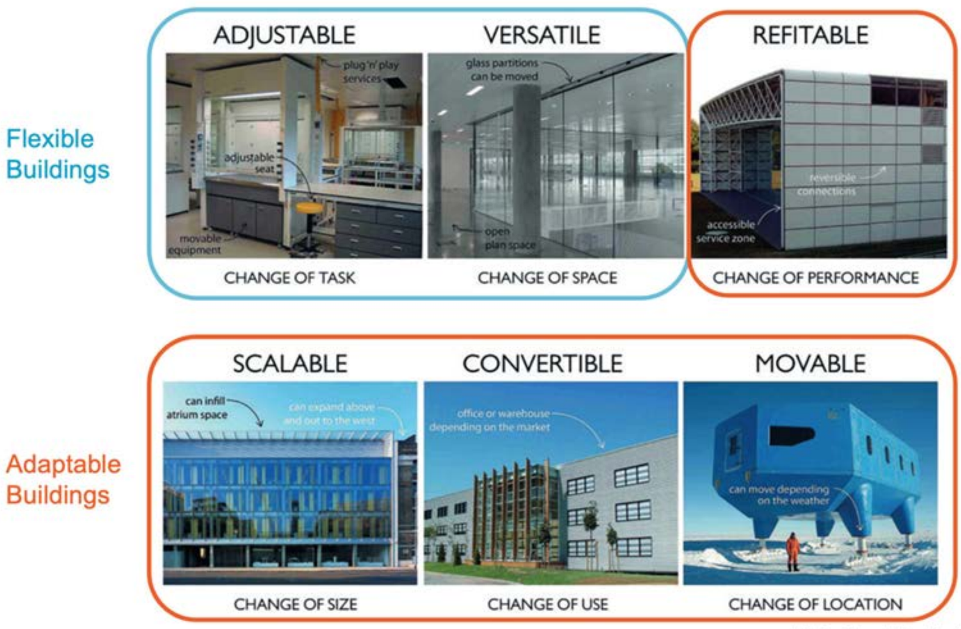

Figure 2 Six Levels of Adaptability by Schmidt and Austin 2016

3 Design for Flexibility and Adaptability

Schneider and Till extensively researched flexible housing projects from 1850 to 2006 located mostly in Europe, the more important of these included as 160 case studies in their book *Flexible Housing* (Schneider & Till, 2007a). They categorised the design of flexible housing into 'soft' or 'hard' types, soft referring to "tactics which allow a certain indeterminacy, whereas hard refers to elements that more specifically determine the way the design may be used" (Schneider & Till, 2007a, p.7). In the soft types, the user can adapt the plan configuration according to their needs, through a more relaxed approach to planning that provides more space and some spatial redundancy, whereas, in the hard types, the architect or designer is in control by designing the dwelling with an intention for its use, for example by providing sliding doors. The authors observed that housing driven by construction technologies was unyielding to change of use other than what it had been designed for (Schneider & Till, 2006, 2007b). Preferring the soft strategies over hard, they discussed a variety of easier-to-implement interventions, such as vertical additions in the roof space, communal circulation space used for other purposes, slack space that can be taken over by residents, functionally neutral rooms, joining two units to make a larger unit, dividing up a unit to make two smaller units, sharing a room between units, positioning of the service core to increase room configurations, and provision of raw space (unfinished space) for residents to finish and customise to their needs (Schneider & Till, 2007a).

Adaptable architecture in the literature has also been referred to by authors as 'loose fit', that allows buildings to change (Lifschutz, 2017), 'hybrid', when it adapts over time (Pelsmakers et al., 2020), 'rhythmic buildings' in a conceptual framework combining the three sustainability pillars of society, environment and economy (Ellen et al., 2022), and resilient housing with creative dwellers (Krokfors, 2017).

But perhaps the most successful architectural movement that provides flexibility for occupants in tall building design is the Open Building movement. An Open Building is designed in two parts: the outer building *support*, or base building, comprising of structural walls, floors, and roof that has a longer life span (100 years); while the non-structural *infill*, which suits the needs of the occupier, has a shorter life span (10-20 years) and can be removed without damaging the base building (Kendall, 2010). This concept aligns with Brand's shearing layers of change discussed earlier (Brand, 1995). The concepts of 'supports' and 'infill' were pioneered by John Habraken and others in the Stichting Architecten Research (SAR) group in the Netherlands, as an alternative approach to the homogenous and inflexible mass housing apartment buildings built after the second world war (Habraken, 1972; Habraken et al., 1976), and in Japan as 'skeleton and infill', by Utida and Tatusumi, in the design of Kodan Experimental Housing Project (KEP) (Ikeda & Amino, 2000) and Century Housing Project (Kendall & Techier, 2000; Minami, 2016). SAR designed a system for dwelling plans in row housing and apartment buildings comprising of fixed structural walls and floors for the perimeter of each dwelling and specific zones for bathrooms/kitchens and living/bedroom areas, which could vary in size according to prescribed incremental dimensions. The architects developed rules for how the rooms could vary in size and function, and created various unit layouts to suit occupant types; however, in early built projects, occupants modified the units in ways not imagined by the architects (Habraken et al., 1976). Consequently, in later Open Building projects, the architects involved end-users in the design process (Kendall & Techier, 2000). More flexibility was achieved in the KEP housing project, where a movable partition wall system allowed occupants to modify the interior - even though some partitions became stiff with age (Minami, 2016).

Contemporary residential Open Building projects are *NEXT21* in Osaka, Japan (Osaka Gas Co, 2013), *Superlofts* in the Netherlands (Habraken, 2017) and 'raw space' housing in *Tila,* Helsinki (Franke, 2014; Koehler, 2022). In *NEXT21* a coordinating architect kept the building skeleton and façade under control by rules stipulating cladding materials and their proportions, without compromising on diversity of apartment sizes, styles and types of households in the building designed by thirteen interior architects for the eighteen infill dwellings (Kendall, 2006; Osaka Gas Co, 2013). Built in 1993, some apartments have already undergone change without any damage to the base building, demonstrating the flexibility of the design approach. In both Superlofts and Tila, the base building has a mostly unfinished double floor apartment space with a bathroom and kitchen finished in Superlofts and only a bathroom in Tila. These three projects are progressive examples of Open Building, an approach that suits the scale of apartment buildings with multiple owners. In all these examples though, flexibility is implemented within fixed perimeter walls and footprint, which may imply high initial construction costs for underutilised.

4 Incremental or Scalable Housing

An alternative approach that plans for future extension of the dwelling is incremental housing, which has precedents in vernacular housing types (Rashid & Ara, 2015). The concept is to build a minimum core as a starter home which is then added on later by the owner as self-builder when household needs change as demonstrated in *Quinta Monroy* and *Villa Verde* by Elemental (Aravena & Iacobelli, 2020). Both housing projects provide a minimum core and space for growth through an organising concept of modular masses and adjacent voids, at the scale of terrace houses of up to three storeys. The owners choose the materials of built-in rooms based on availability and affordability. Each dwelling gains unique appearances providing identity; although the risk exists of lacking consistency, which may result in a haphazard aesthetic.

At the scale of tall buildings, there has been an incremental skeleton-infill approach planned for apartments for low-income families in Malaysia, as discussed in a report (Wook & Mahdzar, 2016). The first phase apartments are designed with adjacent vacant incremental zones that are gradually filled in later; to control the building quality, self-builders are required to use standardised components of partitions, windows, and doors as specified by the architects. Components are designed in module sizes of 1000x2700mm with connection joints that can be attached and detached from their positions, making the components interchangeable (Wook & Mahdzar, 2016).

5 The potential of DfA combined with Design for Disassembly

Increasing on-site adaptability of a building could potentially be achieved by combining DfA with the emerging technology of Design for Disassembly (DfD). DfD could facilitate greater flexibility and adaptability of tall buildings and the CE principles of reducing waste and keeping materials in loops of use. Prefabrication construction has the potential to integrate reversible connections, as the nature of prefabrication is to construct modular, standardised components mostly off-site for assembly of near-finished components on-site (Aitchison, 2018; Geldermans, 2016; Smith, 2010). With reversible connections, building components could be added to and reconfigured on site or at the end of one building's service life, deconstructed and reassembled in another location. However, there is need for research in this still largely unexplored combined field of design for disassembly and design for adaptability of timber buildings.

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Socioeconomic factors for higher adaptability

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1 Introduction

The design of taller timber buildings should be performed with intensive collaboration among the various teams and their members. At present, this makes Circular Economy-aligned, taller timber buildings more demanding than their more traditional concrete and steel counterparts. Unfortunately, the list of design collisions is very long. Here we concentrate on collisions that complicate scalability of funding.

2 Evaluation methods

How do we know if timber buildings retain their value and is there a premium potential?

Historically, both commercial and residential real assets offer attractive risk-return profiles. For timber multi-storey buildings, the historical datasets that would offer the foresight of expected returns are yet to be collected. On the property market, the focus of investor's convenient analysis methods lays with developing, maintaining and improving the rental income as opposed to cost reduction or energy efficiency (Christersson et al. 2015), while discounting effect gives less weight to potential delayed cash flow gains of adaptable solutions (Vimpari 2016). Therefore, the work needs to be done with the investors to bring specific design-related information about physical properties of the adaptable assets (such as lightweight) to the focal point of the investor's decision-making (Vimpari and Junnila 2016).

In the following we give a brief overview of alternative strategies (Figure 1):

- Developing availability of long-term performance data of timber buildings
- Optimizing and aggregating siloed solutions via interdisciplinary collaboration
- Extending learning capabilities and intensifying feedback
- Including finance and insurance in interdisciplinary collaborative optimization

3 Interdisciplinary design collaboration

How do we have one single point of responsibility in interdisciplinary timber design process?

Most building design professionals recognize the benefits of interdisciplinary collaboration for iterative improvement of initial siloed solutions and achieving holistically optimized results. Conversely, the customer is usually faced with a novelty and sometimes wonders who is responsible for the decisions and ultimately the integrity of the timber design. Procurement frameworks exist that enable interdisciplinary collaboration in intra- or interfirm domains. However, the ability to reap benefits of the interdisciplinary collaboration is limited by the availability of the dynamic project leadership expertise in client capacity (Brady and Davies 2010). Such expertise can be educated uniformly to municipal and private sector clients and applied to projects with diverse needs, backgrounds, and timber-based systems (Rodionova 2021). Alternatively, professional construction client, bearing long-term responsibility for the integration of project deliveries and technical property management, can represent a novel single assess point connecting investment professionals and securitizable assets.

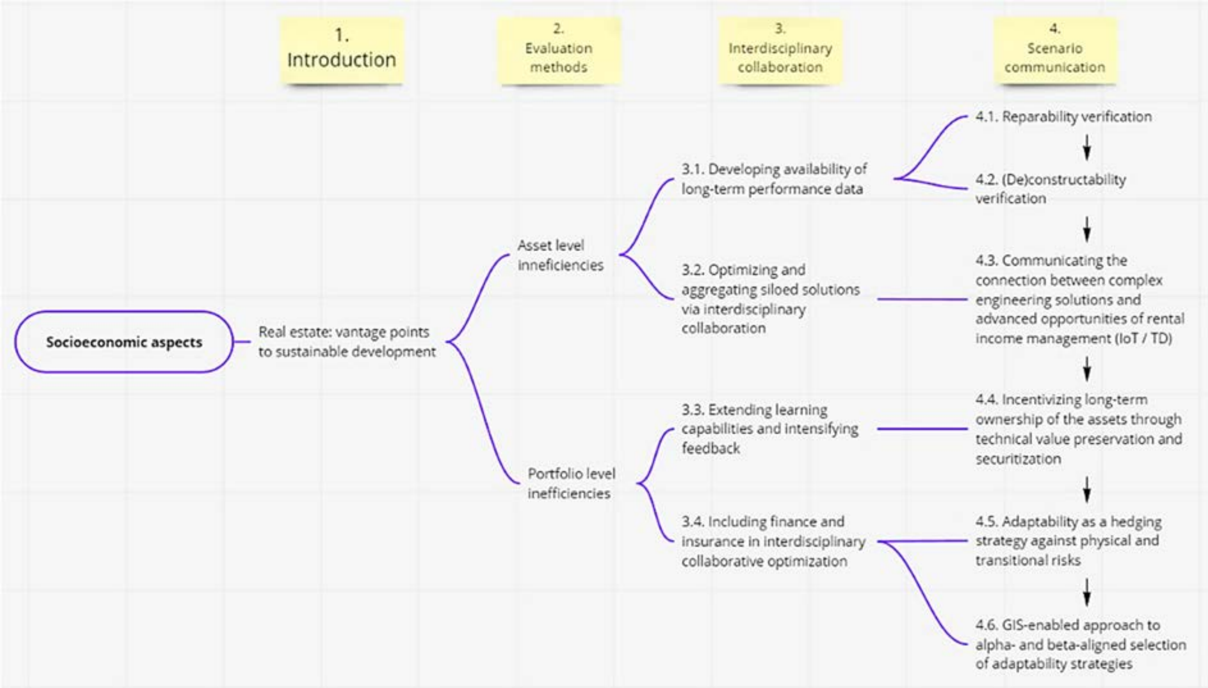

Figure 1: A Mind-Map supporting the report structure.

In the crux of the dynamic project leadership, there is work culture that appreciates the importance of risk recognition and trains project personnel to come forward with the problems identified, as well as offers instructions on how to prevent the threat or take advantage of the opportunity (Davies et al. 2016). While the literature provides guidelines for training teams and members in risk recognition and processing in organizations (Chaleff 2017), developing dedicated training for construction professionals could enhance accurate and efficient risks and opportunities (R&O) communication in projects.

The cultural aspect is augmented with toolsets, including those serving real-time detailed verification of the personnel competence (VTT 2021) and ongoing quality of decision-making, including risk appreciation across the project team (French 2020, Mark et al. 2018, Resolex n.d.). Finally, the incentives and resources should be aligned to support the problem solving. Processes should be put in place to subsidize the innovation emerging from the uncovered issues of the integrated project delivery (and maintenance) through agile cost shifting (Hall et al. 2014).

Development directions in this domain may include standardization of dynamic risk management procedures (Rodionova 2021); including finance and insurance contributions into iterative collaborative optimization (Acharya et al. 2020); and extending learning capabilities and scope of the management from AEC to O&M processes, thus bridging the gap between DfMA and DfD/A workflows (Rodionova 2021).

4 Scenario communication across financial and technical lifecycle design

What is the practical value of Circular Economy solutions and functional adaptability of the timber multi-storey buildings?

As opposed to linear extrapolation or planning found in the conventional asset appraisal methods and overlooking multiple novel sources of volatility (Hirsch et al. 2015, Blundell et al.

2005, Szumilo et al. 2016), scenario planning addresses volatility on two levels. Predictive scenarios consider the iterative nature of built environment projects, while surprising scenarios contribute to the robustness of the general strategy, uncovering hidden vulnerabilities (Galle et al. 2017). We identified following directions of asset and portfolio level research for extended interdisciplinary collaboration between design, finance and insurance professionals. The aim of the proposed framework is establishing dedicated green investment vehicle for multi-storey timber buildings.

Repairability: How do you ensure that your building's bottom line value can be preserved?

- Technical Due Diligence (TDD) of new built projects, evaluating fullness, transparency and validity of the design documentation for the needs of future renovation.

(De)constructability: How to validate adaptability potential of the new design?

- Complementing the above with evaluation framework for obtaining detailed information on individual parts and adaptability routines during O&M stage.

Adaptability: How to best communicate the connection between complex engineering solutions and advanced opportunities of rental income management?

- Digital twin solutions aggregating the complex technical information presented above and allowing for competitive bidding using several alternative use scenarios.

Finder keeper mindset: Is there alternative portfolio enhancement strategies to asset rotation?

- Developing robust long-term asset data management and adaptability strategies towards bundling and securitization of the assets (Eeva 2019).

Transitional and physical risks: How adaptability can help in safeguarding your portfolio against the surprising scenarios of socioeconomic and climate change?

- Due to the volatile nature of the emerging climate and socioeconomic scenarios, different locations have different profiles as related to user profiles and profitability in short-, middle- and long-term. Engineered adaptability can be seen as a way to preserve significant proportion of the assets' physical value even in surprising scenarios.

Diversification of the portfolio: How to define optimal adaptability and green construction scenarios for different locations?

- GIS-enabled analytical approach can augment the selection of appropriate construction technologies, including ratio and location of long-term and interchangeable building components and material bank functionality.

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Designing timber buildings for adaptability

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1 Introduction

Design for Adaptability (DfA) enables buildings to adapt to the changing needs of their occupants and variable conditions of their contexts, thereby keeping them, and their construction materials, in use for longer (ARUP & Ellen MacArthur Foundation, 2018, 2020; Cheshire, 2016; Geldermans, 2016) - while theoretically reducing global warming potential by almost 50% compared to conventional buildings (Rasmussen et al., 2020). Key to DfA is Brand's concept of a building as "shearing layers of change" (Figure 1), which acknowledges different lifespans of building components (Brand, 1994; Nordby, 2009). This concept can be effectively stretched from the functional components of a building to its technological components, where each part, or layer, can be accessed and replaced, for maintenance or spatial re-functionalisation.

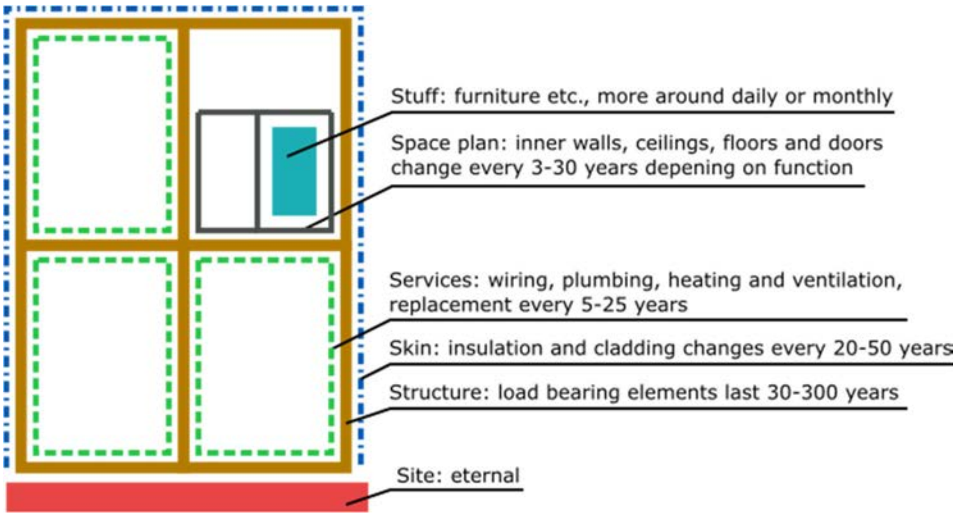

Figure 1. Shearing layers based on (Brand, 1994)*.* (Ottenhaus, 2022)*.*

While DfA has recently gained popularity in literature, it is quite an old concept as buildings have been adapted or repurposed for different uses for thousands of years, including building extensions (Jaksch et al., 2016), modular kit homes used by settlers (Li et al., 2017), as well as relocatable caravans. High-performance adaptability is a more recent concept, where adaptations meet both functional and structural requirements, and the extent of material change required to accommodate functional change may vary significantly.

2 Defining adaptability

Kuiri and Leardini (2022) help clarify the difference between 'flexible' buildings, which allow changes of use to occur without affecting the structure and skin, and 'adaptable' buildings, which require more substantial changes to their physical fabric. Schmidt and Austin (2016) defined six increasing levels of change to the building: from flexible buildings that can be modified by occupants themselves, with little change to the building fabric (adjustable, versatile, refitable), to adaptable buildings, ranging from changing parts or changing the size of the building, to moving the building entirely to another location (convertible, scalable and movable). Therefore, adaptability requires a novel approach to design and construction in the context of a circular economy, to design out waste and keep resources in use. DfA provides framework and strategies to implement reversible changes in buildings.

DfA is enabled by Design for Manufacture and Assembly (DfMA) in combination with Design for Disassembly / Deconstruction (DfD). Modular, prefabricated components with reversible connections allow for partial deconstruction and replacement (conversion, maintenance, and repair), building extensions (scaling), and disassembly and reassembly of entire buildings in a different configuration or location (adaptation, reconfiguration, and relocation) (Akinade et al., 2017; Geldermans, 2016; Nordby, 2009). While past literature has focused on challenges facing taller timber buildings (Buchanan, 2016; Moroder et al., 2018), and the benefits of DfMA (Woodard & Jones, 2020), little research is available on adaptable timber buildings, let alone adaptability of taller timber buildings. According to (Ahn et al., 2022) indeed, most studies focus on environmental benefits of mass timber buildings from cradle to gate, disregarding their circularity potential at the end of life through DfA.

3 Designing timber buildings for adaptability

Working backwards through the adaptability definitions of Schmidt and Austin (2016), the literature on movable timber buildings is mostly focused on low-rise construction, ranging from tiny houses (Calluari & Alonso-Marroquín, 2017), and small-scale demonstration projects (Finch et al., 2020; Roggeri et al., 2021; Smith, Carradine, et al., 2011; Smith, Wong, et al., 2011; Wu et al., 2018; Yan et al., 2022), to temporary accommodation or emergency housing (Badergruber et al., 2016; Baixas & Ubilla, 2016). In addition, some built examples of removable public buildings such as schools, offices and hospitals exist (Kyrö et al., 2019; Newton et al., 2018; Winter et al., 2017). It is also worth noting that while open source building systems such as WikiHouse (Dangel, 2018), Sim[PLY] (Albright et al., 2021), or SE-structure (Montagnana & Fukuta, 2016) allow for disassembly and reassembly in principle, deconstruction can be labour intensive (Boyd et al., 2012; Farrar, 2019), unless disassembly is considered in the initial design (Chisholm, 2012; Walsh & Shotton, 2021).

Scalability of timber buildings is generally only treated in the context of building extensions or urban infill (Dind et al., 2018; Jaksch et al., 2016; Lehmann, 2012), or in the context of single-family homes that can “grow and shrink” in relation to a typical family lifecycle (Milwicz & Nowotarski, 2015; Phillips et al., 2016). Milwicz and Nowotarski (2015) present growing and shrinking homes as a solution to housing affordability, but do not consider the cost of the building site (which is often substantial). Phillips et al. (2016) centre their research around questionnaire results regarding flexible and growing homes in a Brisbane (Australia) context, recommending modern construction technology (such as offsite manufacture) to facilitate changes (such as additions).

Silva et al. (2020) explore case studies of different materiality on movability, scalability, and more permanent internal adjustability. They also propose conceptual architectural solutions for adaptable timber buildings: a shelf structure, where wooden modules can be plugged in and out, a tower prototype that allows internal changes, and a demountable system. Interestingly, while the 14-storey building ‘Treet’ in principle followed the shelf approach with prefabricated modules stacked on “power storeys” (Abrahamsen & Malo, 2014), the external Glulam truss system does not allow for adaptations.

Jockwer et al. (2020) and Walker and Norman (2021) address adaptability in timber construction more broadly. Jockwer et al. (2020) state that the most effective ways to implement circularity in construction are: 1) extension of the service life of both structures and building materials; 2) retention of the quality of materials (durability / longevity of high-quality materials); 3) recycling and repurposing of building parts and materials that no longer meet demands. Adaptability is introduced as a tool to extend the service life of buildings by maximising their use life cycles as shown in Figure 2. This approach is supported by Walker and Norman (2021) who found that highly sustainable (timber) buildings had been "demolished after just 2- years due to a lock of flexibility". They make recommendations to achieve flexibility / adaptability, by keeping the design simple with regular grids, making services accessible and designing for maintenance and repair. They also suggest a similar approach to Silva et al. (2020), where internal walls can be moved by being non-loadbearing. However, this approach would rather fall in the 'flexibility' category according to Schmidt and Austin (2016).

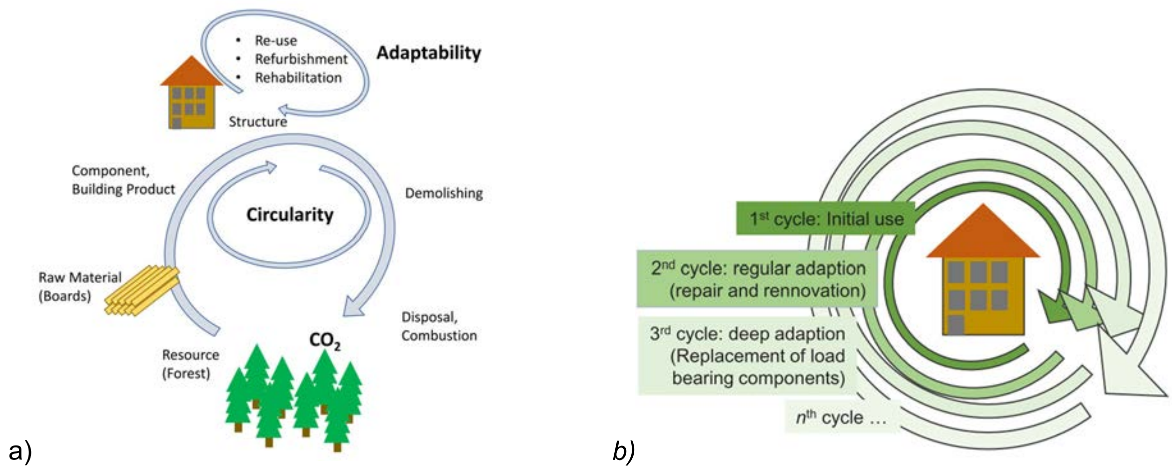

Figure 2. a) Illustration of the concepts of adaptability and circularity. b) Illustration of extension of service life through multiple use-cycles (reproduced with permission from Jockwer et al., 2020).

Jockwer et al. (2020) conclude that DfA allows for buildings to adapt to changing functional requirements, thereby extending their service life, which provides economic, social, and environmental benefits. The authors sum up the idea stating that "[t]he most sustainable building is the building that is not teared down" (Jockwer et al., 2020).

4 Adaptable Taller Timber Buildings: Challenges and Outlook

One of the key barriers to adaptability of taller timber buildings is the lack of reversible connections; mass timber construction commonly relies on a great amount of non-reversible screw fixings. While the connector XRAD allows for structural movability and scalability of cross laminated timber buildings (Bhandari et al., 2021; Pianegonda et al., 2021), all other layers and building requirements are neglected, including hygrothermal performance. Other reversible connectors allow for disassembly of post-and-beam structures (Kowal & Augustin, 2016), however, these systems are not suited for panelised construction (Yan et al., 2022).

Another challenge, and a barrier to implementing adaptability, is the lack of standardisation (Jockwer et al., 2020; Walker & Norman, 2021), since taller timber buildings are currently designed as "one-off" projects (Curtis, 2020). Lack of standardisation also affects reusability of components (ARUP, 2016; Nordby, 2009).

Furthermore, a common 50-year service life means that end-of-life strategies of disassembly, reuse and adaptation are rarely considered during initial design (Geldermans, 2016; Jockwer et al., 2020); this would be an issue for timber buildings and other buildings, alike.

Changing environmental demands due to climate change present a further challenge for taller (timber) buildings, since refitting of the envelope can be difficult (Defo et al., 2018).

Finally, reliable assessment of the remaining service life and performance of salvaged structural members has not been sufficiently developed (Crews et al., 2008; Jockwer et al., 2020; Nakajima & Nakagawa, 2010). This presents a challenge for both scalability and movability of buildings, especially once they have served their initial intended service life.

Addressing these gaps in the literature, current research at Chalmers University of Technology (Sweden) explores adaptable mass timber buildings allowing for change of use and repair of local damages (Bergås & Lundgren, 2020; Ljunge & Silfverhjelm, 2022). Aligned and complementary research at the University of Queensland (Australia) addresses spatial and climate adaptive design of light timber framed construction, with full-scale prototyping (Yan et al., 2022).

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Influential parameters on adaptability of taller timber buildings

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1 Introduction

Timber buildings are becoming more interesting for engineers over the last decade for their multiple benefits in off-site construction, better quality audit, usual modular or simple composition, healthy indoor living environment, low environment impact and other. The basic spatial structure hinders not only communication and productivity but also the adaptability and flexibility from construction point of view to make it possible to continue using the building even if needs have changed (Hegger et al., 2008). If it is a goal to design buildings for long-term usage, it is also possible to expect that functional needs could change through time and that some parts of the building should be replaced. According to Jockwer et al. adaptability can be explained as the possibility to replace or adjust load bearing and other components in buildings in the case of local damages or the change of functional demand. Here two set of parameters can be defined – structural and sociological. First ones are connected to the structural possibilities of the building to adapt – types of joints, elements disposition and relation to envelope, layout etc. and second one to the user demands occurring through usage lifespan.

Before adaption of certain building it is necessary to set series of parameters needed to be assessed in order to make analysis whether a building can be adapted. This set of rules can be bases on occupants reports, layout possibilities (determination by building soft skills and disposition of construction elements, installation shafts, partitions), quality check marks (water leakage, mould growth, infiltration, potential emission of hazard elements done with thermal imaging and air infiltration tests), composition of façade layers, disposition of openings, disposition of HVAC elements and other. Thus, adaptability measures can improve functional organization, structural robustness, aesthetical appearance, and architecture comfort; and can prolong overall life cycle of the building with reducing amount of the waste in construction land fields, reduce energy needed for demolition and transportation.

This paper shows an overview of how different parameters and causes influence on the service life of the building, thus, necessity to adaption and changes in functional and construction properties. It tackles the basis of architecture design principles/ limitations that influence or guide adaptability processes in certain direction.

2 Classification of taller wooden building elements

Adaptability of the building is limited with structural system, envelope system and architectural mass. Each listed item cannot be considered individually, even some of them contain the others, and that is, they permeate each other. According to Green & Tagart, 2017, structural composition of the buildings is categorized into:

- Horizontal and vertical construction element;
    - o frame system, in which loads are carried by system of beams and columns, mostly suitable for building programs that require larger and more flexible interior spaces

  - panel system in which vertical and horizontal loads are carried by a series of regularly spaced solid wall panels arranged in two directions in plan. Panel systems are generally better suited to residential programs, where occupant needs are more fixed
  - hybrid system
- Building core (Ilgın et al., 2022);
  - centrally located – with advantages in structural contribution, compactness, enabling openness of the spaces on the exterior façade for light and views, and better safety performance for fire escape;
  - peripheral - low efficiency in space use, challenging fire escape distances;
- Podium (the lower portion of a building which is distinct from the building mass of the tower) – usual made in concrete, this podium can provide many benefits such as housing services at ground level, providing high clearances in public spaces and large openings, and generating fireproof areas for large mechanical and electrical services and equipment;
- Design of structural system (etc. exposed columns and beams) (Kuzmanovska et al., 2018);

Envelope system depends of structural system, transparency, prefabrication level and architectural expression. The performance of the envelope and the durability of the building are affected by the choice of materials; details of assemblies which must control thermal bridges, the movement of air, vapour and moisture; and quality control of the manufacturing and construction processes, to ensure that the integrity of the envelope is maintained throughout the life of the building. Facades can be categorized as load bearing or non-load bearing. The selection of it is highly connected to both structural strategy and construction sequence. They are divided into three main groups, according to their opaque/transparent ratio degree – (1) opaque walls with punched windows, (2) completely glazed and (3) façade systems with alternating elements either fully transparent or fully opaque. The use of mobile or fixed scaffolding was noted, in order to infer the system's degree of prefabrication of facade. If no action is required from outside during the installation of the façade, the prefabricated envelope system can be defined as factory finished. However, when external access to the façade is necessary the external wall elements can be defined as be semi-finished assemblies. Spatial configuration and architectural mass of tall buildings is tied to the structural strategy; shape, size and location of the core and primary horizontal circulation. Therefore, factors taken into account are (1) building volume (overall geometric strategies such as rectilinear or irregular plan, and regular or irregular extrusion), (2) balcony strategy (wide range of configurations from protruding balcony to no balcony at all, as well as the use of timber as a finish) and (3) circulation (ventilation - central and peripheral, cross ventilation with circulation spaces: totally airtight or with some degree of natural ventilation).

3 Challenges on adapting existing building

The design of today's sustainable building requires integral thinking, where Integral Design process (IDP) enables alternative approaches to be evaluated at the schematic design stage, allows conflicts to be resolved, tracked and approved with help of virtual models. The areas of design expertise overlap and systems within a building perform multiple functions (Green & Tagart, 2017). For instance, size and placement of windows on the façade is not only architectural design concern but it represents engineering task to calculate amount of light it passes through, to calculate potential glare and track infiltration loses on the linear joints between frame and glass, to calculate thermal transmittance and heat loses, develop details of connections, etc. Also, there is a potential conflict with other installation systems such as HVAC, plumbing or electrical networks – the larger glass volume is, less space for building services on the envelope. Today, three-dimensional image of the building makes it possible to identify potential collisions between of any functional and technical elements (Bali et al., 2018) thus make it easier to avoid them. Quality parameters can be considered as sets of rules needed to be accomplished by building for it to be healthy and responsible for the tenants. These parameters are sometimes personal, where users show their own subjective feel of variety of comforts. However, in order to achieve higher standard of built environment they are defined by national or international legislative. Dynamic changes in legislative are also parameter that defines conditions necessary to be fulfilled by the building.

Functional adaptability is determined by microclimate conditions (primarily sun insolation) and technical limitations from architecture practice – structural elements, building services, adaptability of the envelope in accordance with specific needs from the inner space or obsolescence of the materials/joints. Building enclosure acts as environmental separator between inside and outside, and serves to maintain comfortable thermal, visual and acoustic environment within a building. The durability of building itself is determined by the selection of materials, which must be designed for the required service life as well as be compatible with one another in the ensemble. To ensure the integrity of the envelope and long service life of building and facade, the detailing is crucial whereas engineers can control thermal bridging, air, vapour and moisture movement. (Green & Tagart, 2017)

There are several key points that define the level of adaptability of an object. All of them are in some way dependent on each other, but in order to enter the process of change, it is necessary to analyse the existing documentation, the condition of the building and the possibilities of performing interventions. Key factors of adaptability are presented below:

- Building orientation according to properties of micro location (primarily insolation and dominant wind flows) influence on whether floor layout can be adjusted. These limitations are stricter and more visible in the southern regions of Europe with very warm summers, and very cold winters; and they are less visible in the facilities with controlled indoor environment;
- Structural limitations – each type of structure behaves differently. Panel systems are most rigid while skeletal systems enable more adjustments in the floor plans;
- Building services - they present very rigid system of pipes and new connections are determined on distances between utility elements and vertical installation shafts;
- Soft skills – they present potential of the building to adapt to new needs;
- Potential vs. capabilities. Not all good measures for adoption are optimal. Economic parameters are as equally important as others - structural principles, equipment needed, amount of personnel, duration of works, influence on inhabitants and environment impact.

4 Comparing adaptability potential through different case studies

The following chapter presents good practice example where emphasis is given to the parameters which influence the adaptability potential. Student dormitory towers in Trondheim, Norway are made of CLT panels that serve as both partitions and structural elements. Intentionally, this example is chosen because it is not designed with specific necessity for later adaption or changes. It is interesting to question whether present buildings can be adapted in future and to see how functional requirements in early design stages influence the choice of construction that later that determines possibility of adapting the building with regard to function, structure and envelope and the installation systems in the building (whether it is open or hidden arrangement).

This example is determined by both primary structure and the envelope, which are load-bearing elements. As the main purpose is student housing which required small individual rooms, they are divided by CLT panels as load-bearing element. In that case, adaptability (in this sense flexibility to) is only possible by making new openings in the panels what can weaken the structure. Adaptability potential of the buildings which are built with CLT panel system is not great, since they have not been designed with that purpose. Joining two unites to one bigger apartment will potentially be possible, however, that will demand significant efforts of load redistribution and joining two separate bathrooms will demand different arrangement of installation systems.

Building installations (air conditioning, plumbing and electrical in some parts) are put beneath ceiling (noticeable from ground floor common areas) making them easily reachable for repairs. This type of installation allows for horizontal pipes to be rearranged/redirected without compromising structural integrity of the floor slabs.

Figure 1. Open installation management system in Moholt tower – ease of access, maintenance and rearrangement potential (photos by S. Slobodan Peulić).

5 Conclusion

This paper showed brief set of parameters needed to be evaluated when adaptability is analysed. Its contribution is in promotion of the building adaptive skills and emphases that a building can be adaptable mostly if it has been thought/ designed as such. Moholt example is taken due to very precise function, heavy usage and different social structure. This is good example of timber structure that has peaks in usage during semester and that is empty during summer and winter breaks. Trends are moving towards column and beam/slab systems despite the program; a shift towards the hybridization of constructive materials; increasing the articulation and expression of wooden structural elements and wooden ceilings; increasing use of non-wearable sheath systems; an increase in the use of fully glazed facades and, potentially, a move towards increased prefabrication of the envelope. Further analysis could investigate comfort quality within the building and analyse adaptability from more detailed point of view looking into details and whether rearrangement of interior and exterior elements can be achieved.

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Parameters for wooden adaptive facades

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1 Introduction

Requirements for the envelopes of buildings being built in the 21st century include that the envelopes be made of materials that are not harmful to the environment or human health, and that the production and construction processes be with low energy requirements and minimized emissions. It is important that they provide the necessary functionality and comfort of living in the building, and that they have a long lifespan that finds adaptability to the various and diverse changes that occur throughout the building's lifetime.

The adaptability of building envelopes can be considered from different aspects, and accordingly, different parameters for design and assessment can be established. For the design of facades in general, and thus wooden facades, several parameters can be recognized in terms of adaptability:

- adaptability to annual and daily cycles, i.e. changes,
- adaptability to new technologies, especially the integration of energy production technologies into facade structures,
- adaptability to the needs of improvement of spatial comfort, the possibility of removing and replacing non-load-bearing parts of the facade and adding new structures in order to expand the existing interior space or create balconies and loggias,
- adaptability to changes in design and construction standards and regulations (requirements for thermal insulation, fire resistance, safety, etc.),
- adaptability to the different needs of users in terms of participation in the creation of facades, which will represent the individual expression of each user on part of their facade, which has so far been realized in rare cases when it comes to multi-story buildings.

On this occasion, attention will be paid to the first two parameters, considering that they are directly related to the development of new facade technologies, energy saving, and thus the reduction of environmental pollution.

2 Adaptability to annual and daily cycles

Facade concept and structure should be designed to provide satisfactory user comfort, so in order to achieve high living and working comfort, advanced facade technologies are being developed that allow adaptation to the changing external environment (Furundžić et al. 2018), specifically, the annual and daily changes.

Adaptive facades are characterized by changeable appearance as a result of adaptation/response to daily and annual changes in the environment. Depending on the technology, there are mechanical and dynamic/kinetic facades.

Dynamic/kinetic facades are usually incorporated in, i.e. built into the building structure, and consequently they have to be part of the design idea from the beginning. In terms of functioning, there are three types: facades with smart material, intelligent dynamic facades and responsive dynamic facades, and in the case of these concepts, people have no direct influence or contact with the elements from which the facades are made.

When it comes to wooden facade components, their use is observed in the case of mechanical adaptive facades. Mechanical adaptive facades contain elements that are being moved by human command and/or hand and thus adapt to the needs of the users. The concept is characteristic for adapting the facade to the function of protection from solar radiation. The design of mechanical adaptive facades differs depending on the orientation of the facade, and the types differ depending on the position/orientation of the elements, the shape/type of elements and the mechanism of actuation/movement in the function of adapting to changes in the environment (Figure 1).

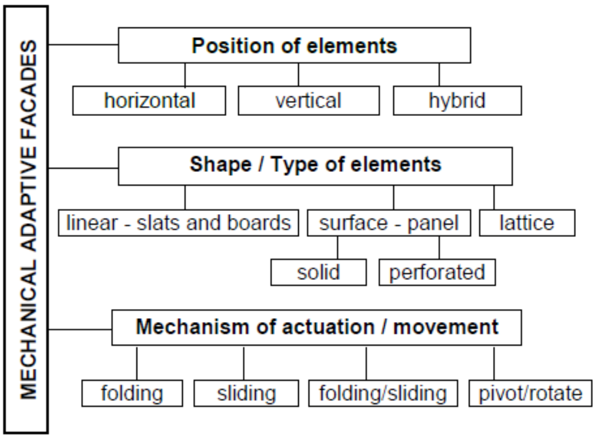

Figure 1. Design parameters of mechanical adaptive facades (image: A. Krstić-Furundžić)

Figure 2. Vertical folding/sliding wooden components of the adaptive facade of the housing block in Wroclaw, Poland (image: A. Krstić-Furundžić 2017)

Figure 3. The sliding wooden components of the adaptive facade of the housing block in Wroclaw, Poland (image: A.Krstić-Furundžić 2017)

Figure 4. Panels made of solid boards as wind protection (rotate along the vertical side axis), Trondheim, Norway. Left: the appearance of the building, right: facade detail (image: A. Krstić-Furundžić 2006)

Regarding the position/orientation of elements, horizontally and vertically oriented elements are distinguished. Horizontal ones are characteristic for the southern orientation of the facade, while vertical ones are used for the eastern and western orientation of the facade. Their combination is also possible - hybrid forms. Shape/type of elements can be linear – slats and boards, and surface – panels, while in terms of processing panels can be solid or perforated, which strongly affects the visual experience of the appearance of the facade and building. Panels constructed from a frame into which slats are inserted are often used, which provides protection from solar radiation, good daylighting of the interior space, as well as a view of the exterior space (Figures 2 and 3). The mobility of the slats contributes to a better response to changes in the environment. Panels formed from solid boards are usually used in windy areas when they serve as wind protection (Figure 4). Actuation/movement mechanisms are folding, sliding, folding/sliding, pivoting/rotating. Usually, the wooden elements are attached to the facade via a metal substructure and are located at an appropriate distance from the insulating layer of the facade. There are various systems for hanging wooden elements for the substructure, which can be visible to a greater or lesser extent, affecting the appearance of the facade. The fastening system of wooden elements must be designed in accordance with the types and intensity of loads that occur due to the weight of wooden elements, the effect of wind and thermal stresses, as well as occasional stresses due to fires or earthquakes.

The design of high-performance facades is unavoidable in contemporary architectural practice as a key trend in achieving environmentally responsible buildings, as well as buildings that enable the well-being of users. This approach is also noticeable when it comes to wooden facades and buildings. „The performance of building envelopes hugely relies on their response to their changing environment. More comprehensive understanding of the combination of forces affecting a building envelope requires designers to create more flexible and responsive solutions. These responsive solutions involving technologies such as microprocessors and actuators entail collaboration with other disciplines of mechanical and electrical engineering, computing, physical and social sciences. Therefore, design of high-performance building envelopes is a good example of interdisciplinary practice in architecture resulting in improved efficiency and performance in buildings“ (Tashakori 2014).

3 Adaptability to new technologies

In conditions of energy deficit and increasing energy prices, the need to use renewable energy sources and reduce environmental pollution, the building envelope is recognized as a position for locating devices with advanced technologies for energy production. The facade, as the component of the building that is most directly exposed to the sun and wind, is the most effective site for innovations in energy savings and alternative energy generation (Velikov and Thun 2012).

The integration of energy production technologies into wooden facade structures is the subject of many scientific researches and experiments. Different solutions are present in terms of developing technology and devices for the production of thermal and electrical energy. Solar thermal collectors (STCs) are devices for the production of thermal energy, while photovoltaic modules (PV modules) are devices for the production of electricity. In both cases, stand-off or add-on and building integrated devices are available, and the application of each of them has a different effect on the appearance of the building. Add-on are independent devices applied on roof or facade structure, while building-integrated are building components which can substitute conventional roof or facade cover materials (Krstic-Furundzic et al. 2017). Hybrid PV/T facade concepts are also available. The unique quality of prefabricated wooden facade wall panels with integrated solar thermal collectors (BISTC) and PV modules can be achieved by factory production. Assembly is easier and takes less time.

The wooden structure of the facade can be a substructure for carrying glass panels with integrated PV cells, i.e. PV modules, whereby the facade, in addition to the function of closing and protecting the interior space, also has the function of generating electricity and protecting against solar radiation, which makes this facade multifunctional (Figure 5).

The outer layer of STC and PV module is transparent and mostly made of glass plate. That is why the facade looks like a glass facade, which camouflages that it is a wooden structure of the facade. The appearance of solar thermal collector and PV module, as a building component, is determined by the material, surface texture, color and type of jointing. The color of solar thermal collector depends on absorber color or selective filter color, while the color of the PV module depends on the type of PV cells and/or the color of the antireflective layer.

Figure 5. Facade of wooden structure with integrated PV modules, The Academy of Mont Cenis, Herne, Germany. Left: the appearance of the building, right: facade detail (image: A. Krstić-Furundžić, 2019)

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SG Design for disassembly and reuse

Designing timber buildings for disassembly and reuse

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1 Introduction

Research, frameworks and experimental projects addressing building design that embraces Circular Economy (CE) principles have multiplied in the last few years (Munaro et al., 2020), including guidelines for 'circular design', a term clearly outlined in Cheshire's *Building Revolutions* (Cheshire, 2017) and the *Circular Design Guide* by Ellen MacArthur Foundation (2018). Key to understanding circular building design is Brand's concept of building as "shearing layers of change" (Figure 1), which acknowledges different lifespans of building components (Brand 1994; Nordby 2009). This supports a systemic approach to building design, where each component of the system is integrated and yet replaceable to accommodate functional and spatial changes of the building (and its users) over time. Conceiving and designing a building in layers combined with Design for Disassembly /Deconstruction (DfD) allows for maintenance and repair, as well as salvaging of building components at the end of life through disassembly and reuse in the same or a new context (relocation, adaptation, modification) (Akanbi et al., 2018; Nordby, 2009). While the focus of this report is on structural systems, assemblies, and components, many principles of disassembly and reuse can equally be applied to the building envelope, building services, and other non-structural elements (Finch et al., 2021; Michael, 2020; Stephan & Athanassiadis, 2018; Wasim et al., 2020).

2 Design for disassembly and reuse

DfD was introduced across many industries to facilitate maintenance and repair of products (Akanbi et al., 2019; Bogue, 2007; Boothroyd & Alting, 1992; Boothroyd & Girard, 1996a, 1996b; Desai & Mital, 2003; Smith et al., 2012, 2016). Boothroyd and Girard (1996b) propose DfD guidelines for the product structure (functional units, easily accessible and easy to (dis)-assemble) and materials (few identifiable and separable materials, non-harmful and recyclable). Bogue (2007) defines DfD rules for a product structure (modularity, standardisation, minimise components / variants), materials (mono materials, recyclable),

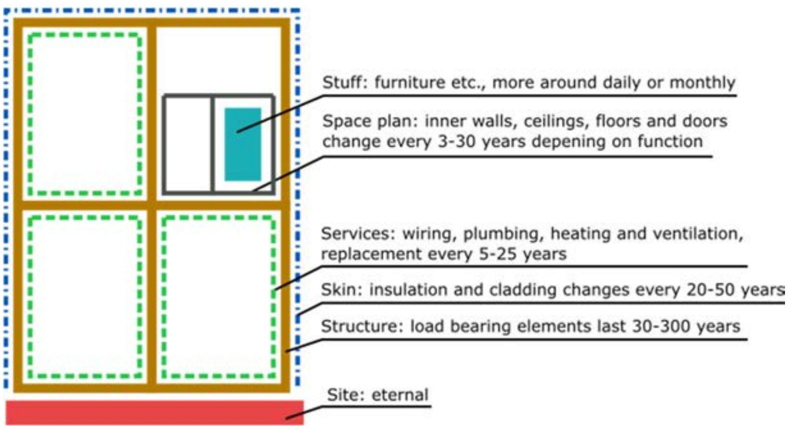

Figure 1. Shearing layers based on Brand (1994). Source: Ottenhaus (2022).

connections (minimise number of joints, accessible and visible joints, easy to disassemble, fasteners instead of adhesives), component characteristics (lightweight, robust / durable, non-hazardous), and disassembly conditions (automated, no specialised procedures or tools). Smith et al. (2012) provide further design rules for 'green products' that allow for selective disassembly of components for repair, reuse, recycling, or remanufacturing. The rules include easy disassembly, single-translation motions, removal of components and fasteners from a single direction, boundary components (layers) that can be easily removed and in the same direction as target components (i.e., those that frequently require maintenance), placing target components close to the boundary and close to each other. All these design rules can be applied to buildings as products.

In building construction, both terms Design for Deconstruction and Design for Disassembly are used interchangeably. DfD is often seen as a progression from Design for Manufacture and Assembly (DfMA), a well-known concept in modular offsite construction (Akanbi et al., 2018, 2019; Akinade et al., 2015, 2017). Crowther (1999) notes that DfMA and DfD have been used throughout history, e.g., in the design of kit homes of British colonies. Crowther also makes recommendations for a multitude of circular design strategies that are enabled by DfD, such as materials recycling (fewer materials, avoid hazardous and toxic materials, mono materials in inseparable sub-assemblies, avoid finishes and coatings, permanent material identification), component reprocessing and reuse (minimise number of components and wearing parts, use mechanical connections, open buildings, building in layers, ease of access, tolerances, standardised connectors, permanent component identification), and building relocation (standardisation, regular grid, lightweight material and components, DfD).

While Crowther (1999) sees DfD as an implicit enabler of material, component and building reuse, Nordby (2009) uses the term 'salvaging' to describe DfD with the purpose of reuse. Nordby also synthesises DfD literature for building construction: Berge (2007), who investigates design for assembly and disassembly principles, which are separation of layers, possibilities for disassembly within each layer, and use of standardised monomaterial components; Fletcher (2001), who introduces 27 DfD principles at system level (adaptable buildings), product level (refurbish, repair, replace), and material level (reuse, recycling, cascading / degradation); Thormark (2001), whose thesis focuses on "Recycling Potential and Design for Disassembly in Buildings"; Sassi's work on closing resource loops within circular economy frameworks (Sassi, 2002, 2004); Crowther (2003), who introduces 27 DfD principles for industrial design, architectural technology, buildability, maintenance, and research; Durmisevic (2006), who lists 37 DfD principles at building, system, and material levels; and Brand's shearing layer concept (Brand, 1994). Nordby also derives the following salvageability criteria:

- **Limited material selection**, i.e., minimise types of material, use mono-material components that allow for separation at end of life, reduce types of components and connectors, e.g., through standardisation, and avoid toxic or hazardous materials and secondary finishes, which, again, affect disassembly and end of life scenarios.
- **Durable design**, i.e., long-lasting components with adequate tolerances to withstand repeated dis- and re-assembly and reuse, thereby lasting several building lifecycles.
- **High generality / standardisation**, e.g., standardised dimensions, modular construction (prefabrication), and a standardised structural grid, combined with small(er) and lightweight components for easier handling, and reduction of complexity of components and assemblies such that common (standardised) tools and equipment can be used.

- **Flexible connections**, i.e., the use of accessible reversible connections for subassemblies, between components and between building parts, allowing for parallel disassembly and reassembly.
- **Suitable layering**, by designing structurally independent functional layers arranged according to their expected technical service life (Brand, 1994).
- **Accessible information**, that provides information about material and component types, provides updated as-built drawings, log of materials used and guidance for deconstruction, and identifies and provides access to connection points. Present day examples are digital twins (Qi et al., 2018) or material passports (Heinrich & Lang, 2019).

Sanchez et al. (2020) and Sanchez and Haas (2018) define further rules to plan (partial) disassembly of buildings. Durmisevic (2019) gives design strategies and technical solutions for reversible buildings as part of the Buildings as Material Banks (BAMB) project.

While DfD has been embraced as a key design strategy to enable circularity in the built environment (Akanbi et al., 2018, 2019; Akinade et al., 2015; Cruz Rios & Grau, 2020; Geldermans, 2016; Minunno et al., 2018; O'Grady et al., 2021; Walsh & Shotton, 2021), Akinade et al. (2017) highlight that non-technical factors, such as policy and legislation, and a change in design thinking need to be addressed to enable DfD.

3 Additional requirements for timber buildings

In timber buildings, DfD is often enabled by reversible connections (Akinade et al., 2015; Boyd et al., 2012; Klinge et al., 2019; Nordby, 2009; Sparandara et al., 2019; Yan et al., 2022). Ljunge & Silfverhjelm (2022) investigate the potential reuse of structural CLT panels with respect to inter-panel joints. They highlight issues related to reversible joints (i.e., lack of technical solutions), as well as technical challenges in the removal of CLT panels itself with respect to the motion and access required. Hence, design for disassembly and reuse requires careful consideration at early design stages to enable multiple reuse cycles (Forsythe, 2011; Kuiri & Leardini, 2022).

Direct reuse of timber components, such as beams, columns, or panels, is only possible if the components are intact, including parts of joints that are permanently attached (Nijgh & Veljkovic, 2019). This means the timber itself needs to be free from damages or decay that affect functionality, which can be challenging to assess for older reclaimed timber components (duration of load effects), thus requiring regrading (Crews, 2007; R. Falk et al., 1999; R. H. Falk & Green, 1999; Nakajima & Murakami, 2007). Alternatively, components should have only sustained an acceptable amount of damage that can be repaired or does not affect functionality (Celadyn, 2019). An example of reuse with lower functionality would be recycled timber that has been down-graded, whereas an example of reuse after acceptable damage would be timber elements with sacrificial joints (fuses) that can be replaced while the member itself remains intact, which is common practice in low-damage seismic design (Blomgren et al., 2018; Holden et al., 2012; Sarti et al., 2013). If reuse in a similar configuration or functionality is not possible, timber materials can be cascaded, i.e., cross from the technosphere into the biosphere, where they are reprocessed into engineered wood or fibre products, as shown in Figure 2.

Finally, some reuse scenarios may require a timber structure to retain its performance despite frequent reassembly cycles. Examples are temporary structures such as scaffolding or emergency housing. In those cases, it is crucial that timber joints retain their initial stiffness and tolerances, i.e., limit embedment deformation that creates slip (Reynolds et al., 2018).

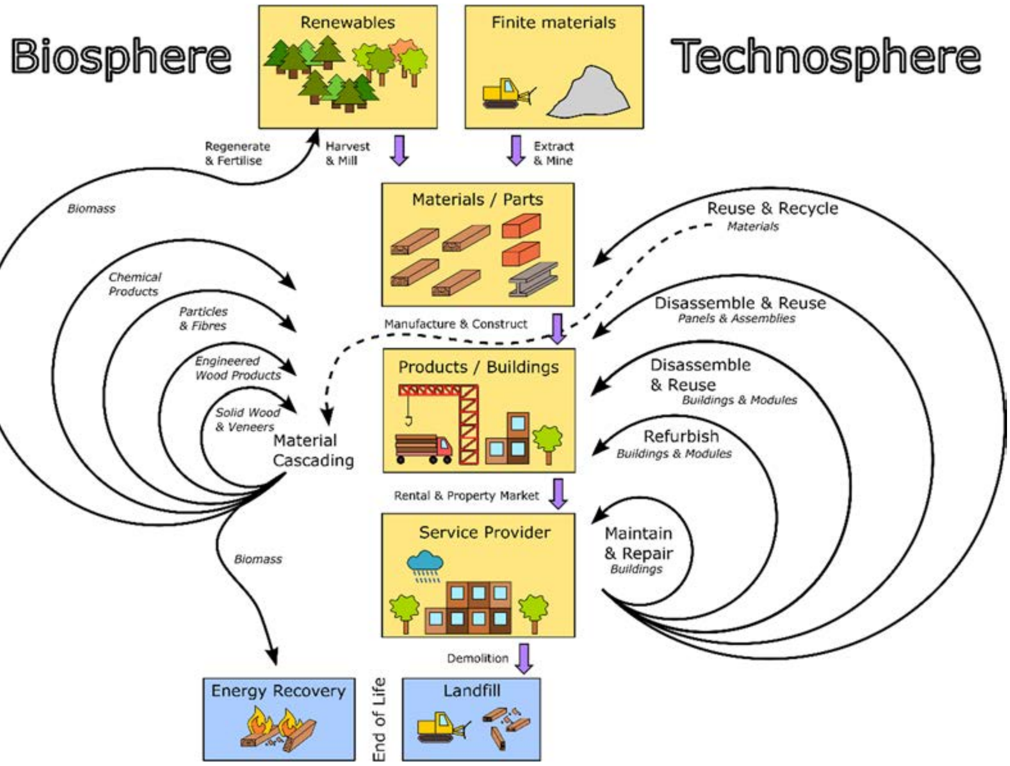

Figure 2. Butterfly diagram of circular timber buildings (Ottenhaus, 2022b). *Adapted from Ellen MacArthur Foundation's "Butterfly Diagram"* (Ellen Macarthur Foundation, 2019).

4 LCA of timber buildings designed for disassembly and reuse

Finally, it is worth assessing the lifecycle impact of reuse. Often, durability enhancing measures, such as chemical timber treatments, are associated with a higher environmental footprint but higher reuse potential. Buyle et al. (2019) undertook consequential Lifecycle Assessment (LCA) and Lifecycle Costing (LCC) for different internal wall assemblies to assess circularity potential. Seven wall assemblies were assessed over a period of 60 years, with a refurbishment every 15 year. Low lifecycle impact was achieved both for assemblies that are designed to be used again and have a higher initial impact, such as a plywood boarding connected reversibly to a demountable metal frame substructure, as well as for assemblies with no possibilities for direct reuse that have a low initial impact, such as a drywall system with a wooden substructure. Eberhardt et al. (2019) came to a similar conclusion after conducting a LCA case study on a Danish concrete building designed for disassembly. Their findings show that substituting concrete with conventional timber construction still leads to higher CO_2 emissions savings than a concrete building designed for disassembly and reuse. Nevertheless, Akinade et al. (2015) recommend that "[i]n the case of timber structures, not only the use of prefabricated assemblies and demountable connections must be considered, but also the durability of the wood. This is to enable the reusability of timber components because wood has more value in reuse than in recycling."

Buyle et al. (2019) found that key to incentivising reuse was shifting environmental burdens upstream, by taking environmental consequences of design decisions into account.

5 Summary

In summary, Design for Disassembly/Deconstruction (DfD) is essential to enable maintenance, repair, adaptation, and reuse of timber buildings. DfD is generally enabled by reversible connections and research is needed to further develop timber connections for repeated assembly and disassembly without loss of performance. Reuse of timber components has further requirements regarding timber durability, limited wear and tear, and reliable assessment of the remaining service life due to duration of load effects.

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Circular material flows for timber buildings

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1 Introduction

The greatest innovation potential to re-shape construction practice for a circular economy is at the design stage, through a paradigm shift in the way buildings are conceived: as long-lasting yet temporarily artefacts that can be easily reconfigured, for flexible use, or disassembled into reusable components and materials. Extending a building's service life and keeping its materials in use for longer are both key to designing out waste and reducing resource consumption. Timber stores carbon dioxide (CO_2) while in use; the average tree absorbs 10 kg of CO_2 per year for the first 20 years (Bernal et al., 2018), which presents a case for using responsibly harvested wood in timber building construction. Since both decomposition and incineration release the stored CO_2, extending the life of a timber building and its parts is an effective way to implement circular principles in construction. However, current end-of-life (EOL) options for timber buildings are usually considered from a biosphere perspective, with a focus on cascading or energy recovery - which releases the stored carbon (Campbell, 2018).

This paper explores literature that addresses design principles for implementing CE principles in timber building construction to maximise their sustainability potential through carbon sequestration and value retention across multiple use cycles. While the literature focuses on different typologies and scales, most principles are applicable to low-, mid-, and high-rise construction alike.

2 Designing timber buildings for circularity

The following section is a non-exhaustive state-of-the-art literature review of available frameworks and methods to establish circularity for timber buildings. The review is based on a literature study conducted in early 2020 using the keywords *circular** and *timber OR wood* in a Scopus query. It should be noted that circular building design includes many concepts such as *Building as Materials Banks* (BAMB)[1], material passports (MPs), urban mining, design for adaptability, disassembly and reuse, maintenance and repair, etc., but not all of them are discussed here. This review rather focuses on material flows for timber buildings.

2.1 Circular economy frameworks and the building industry

The Ellen MacArthur Foundation (EMF) "works to accelerate the transition to a circular economy" (EMF, 2022). In collaboration with partners, the EMF has released guidance and reports on CE principles in the built environment.

McKinsey (2015) introduces the ReSOLVE framework, which includes six actions for the implementation of CE principles:

- **Regenerate**, shifting to renewable energy and materials
- **Share**, thereby slowing product loops, design for durability and reuse
- **Optimise** performance and efficiency, reduce waste
- **Loop**, keeping components and materials in closed loops and minimise those loops

[1] *Buildings as Material Banks (BAMB) is a circularity concept and the title of an EU Horizon 2020 research project.*

- **Virtualise**, rather than making physical things
- **Exchange** by replacing old materials with new advanced materials and technologies

ARUP (2016) applies the ReSOLVE framework to the built environment and integrates it with other concepts such as Brand's shearing layers (Brand, 1994). The publication evaluates over 40 case studies using the ReSOLVE framework.

A later report by ARUP and Ellen MacArthur Foundation (2018) presents a roadmap towards a CE in building construction and use and identifies three key stakeholders to enable the transition: policymakers, investors, and construction clients. It is the first part of the *From Principles to Practices* collaborative project between ARUP and the EMF.

The second part of this collaborative project by ARUP and Ellen MacArthur Foundation (2020) introduces five new circular business models for real estate: **Flexible spaces** that allow for multi-use of the same space; **Adaptable assets** for alternative use case scenarios either due to changing market conditions and/or social expectations; **Relocatable buildings** that allow for temporary use at different sites using modular, deconstructable buildings; **Residual value**, where building materials retain value at deconstruction; and **Performance procurement**, i.e., product-as-a-service business model scaled up to whole building systems.

Geldermans (2016) highlights that CE and Cradle-to-Cradle frameworks imply radical changes for the construction sector and puts forward the concept of 'buildings as material banks', where high quality monomaterials are employed together in a system that anticipates their reuse and regeneration. Geldermans discusses 'design for adaptability' as a strategy for extending a building service life, and touches on EOL concepts such as 'design for disassembly' and 'design for recycling'. Geldermans also provides an example inventory matrix that captures building layers (shearing layers), material turnover rates (lifespans) and regeneration routes (reuse, recycling, reprocessing) for those layers in the technosphere or biosphere. Geldermans (2016) highlights the need to approach circularity not only from a technical viewpoint but to integrate environmental, societal, and economic factors.

2.2 Urban Mining and material cascading

Given the environmental credential of timber as a renewable material with carbon sequestration capability, EOL options for timber buildings and components are considered in practice mostly from a biosphere perspective. However, the literature reveals research focusing on its potential reuse and recycling.

Mair and Stern (2017) review and contrast circular economy (CE) and cascading utilisation (CU) of wood products in literature between 1990 and 2016. First, the two concepts hardly appear together in the same publication, which may be owed to the fact that CE and CU are used in different contexts as shown in Figure 1. While the CE includes considerations of many kinds of resources, publications on CU include a stronger focus on bio-based materials (such as timber). CU mostly refers to the use of resources from high- to low-value products, where the bio-resource is effectively down-cycled (cascaded). In contrast, the CE focuses on how to keep the resources in the system and minimise the use of primary resources. The paper concludes that CU addresses primarily resource management whereas the CE provides a more holistic approach. In consequence, CU should be considered a basic concept within a CE framework and particularly in the circular bio-economy (biosphere), in which investigations are performed on raw material efficiency performance over multiple-use phases.

Honic et al. (2019) present a proof of concept for material passports (MPs) for a residential building designed of either timber or concrete. In the study, the "MP acts as a design optimisation tool, as well as an inventory of all materials embedded in a building and displays the recycling potential and environmental impact of buildings". The study finds that while mass timber has a lower recycling potential than the concrete option, the concrete building generated more waste overall. Furthermore, lifecycle assessment showed that the timber option performed better than the concrete option. The paper recommends using a material with a long lifespan (durability) and high reuse potential. MPs can then facilitate urban mining "where existing stocks serve as a source of secondary raw materials" and be used as a decision-making tool in the whole value chain.

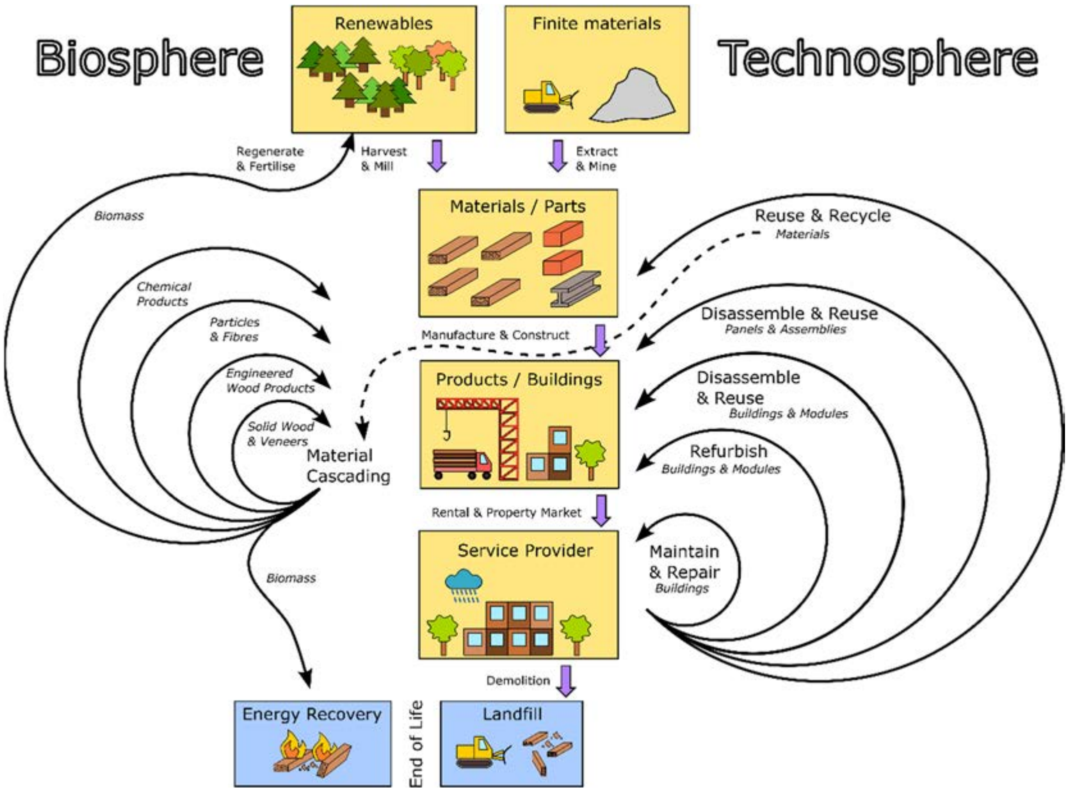

Figure 1. Timber material and component flows within the technosphere and biosphere (Source: Ottenhaus, 2022a).

Deetman et al. (2020) model construction (inflow) and demolition (outflow) of building floor space for both residential and service-related purposes as global annual demand for construction materials as well as an estimation of the availability of waste materials after building demolition. The paper projects that, by 2050, only 55% of construction-related demand for copper, timber, and steel could potentially be covered by salvaged building materials. This shows that urban mining alone cannot cover the growing demand for construction materials.

Romero Perez de Tudela et al. (2020) present a method to estimate the timber stock in residential buildings in London pre-1992 which is based on secondary data from external research bodies, national statistics, and a housing stock management database. The paper finds that, generally, there is more timber in floors and roofs, and in older buildings. The presented method is a valuable tool when BIM is not available and capable of contributing to the growing understand of existing buildings as material banks.

Höglmeier et al. (2013) explore wood waste cascading from demolition waste in 2011 in south-east Germany. They find that 45% of the recovered wood is potentially suitable to be cascaded in particle- or fibreboard production, 26% would be suited in a reuse scenario, and 27% could be channelled into other high-value secondary applications. However, challenges in certification for structural application are highlighted.

To ensure safe and reliable use of reclaimed materials, they might need to be regraded or reclassified (Crews, 2007; Nakajima & Murakami, 2007). This is especially important for materials salvaged from older buildings for which information about their original grade or quality is often missing (Forsythe, 2011). Reclaimed timber materials may also suffer from biological or environmental degradation, as well as duration of load effects (Hartnack & Rautenstrauch, 2005; Smith & Foliente, 2002).

Rasmussen et al. (2019) examine the feasibility of reusing construction materials and showcase a Scandinavian company offering three building products based on reused materials, windows, wood cladding, and concrete. The analysis shows that reuse is price competitive and leads to significant reductions in environmental impacts. Likewise, Klinge et al. (2019a, 2019b) and Roswag-Klinge et al. (2019) showcase how to reuse timber elements and materials from existing buildings, using waste wood as a resource.

Crowther (2003) and Nordby (2009) stipulate design criteria to increase reuse potential. To allow reuse of timber components, they need to be intact, including parts of joints that are permanently attached (Nijgh & Veljkovic, 2019). Alternatively, components should have only sustained an acceptable or repairable amount of damage, unless they can be reused in a way where the damage does not limit the functionality (Celadyn, 2019).

3 Opportunities for timber buildings in a CE

In the binary approach to material flow discussed above, either within the biosphere or the technosphere, timber buildings present, indeed, a challenge, as they sit at the interface of both spheres. When timber materials are only considered for cascading, processing cost in manufacture and construction are neglected, both monetary and in terms of emission and environmental impacts. Furthermore, cascading of waste timber can be impacted by durability measures, such as chemical treatment, and impurities, such as fastener remnants or paints (Faraca et al., 2019, Heräjärvi et al., 2020), which reduces the effectiveness of this approach.

Figure 2 illustrates how the CE not only offers opportunities in the biosphere through cascading or recycling of timber materials and fibre, but also in the technosphere through repair, maintenance, reconfiguration, adaptation, disassembly, and reuse of timber buildings, as well as their components and materials. Both spheres need to be considered holistically to maximise circularity potential and minimise product and resource loops (Jarre et al. 2020).

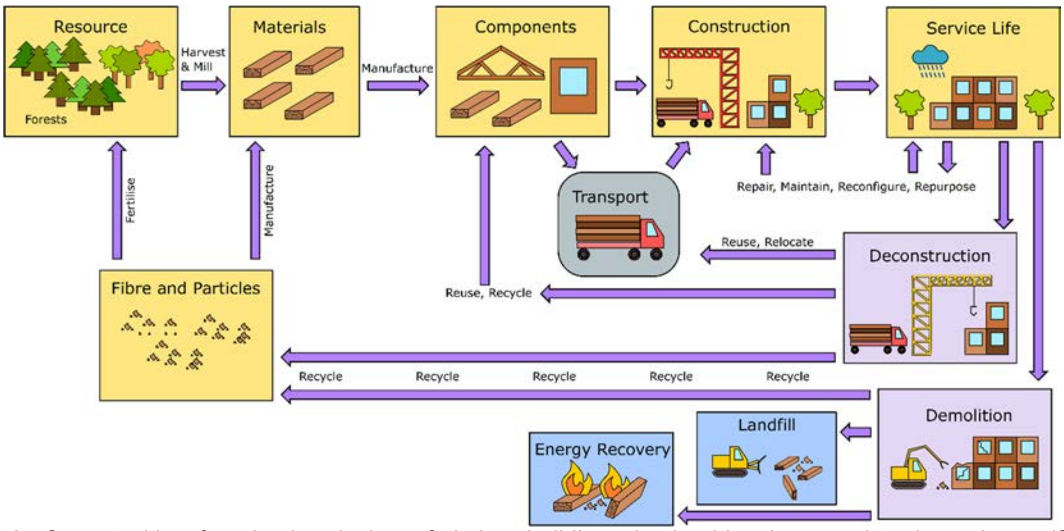

Figure 2: Opportunities for circular design of timber buildings in the biosphere and technosphere. (Source: Ottenhaus 2022b).

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Properties of salvaged structural timber components: How to account for long-term loading effects given unknown load histories?

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1 General remarks

In order to reuse salvaged timber for structural purposes it is necessary to establish the remaining mechanical properties for the next service life. Generally, timber members need to be regraded / recertified / reclassified according to a standardised procedure before they can be reused. This needs to be done irrespective of the intended reuse configuration or application; the certification has to apply whether the component is reused in its original shape, quality and dimension, or serves as raw material for the production of new structural timber products, e.g. by cutting boards from large-dimensional beams as base material for glulam or other products. Establishing such reclassification procedures appears even more challenging than grading of new timber as there are some additional unknowns. One of these unknowns is the origin of the source material which may play an important role in the grading process, e.g. with respect to grade or strength limits. Furthermore, the original species might be unknown and assigning the correct timber species difficult (Crews 2007; Falk et al. 2008).

2 Effect of damage and imperfections

Another unknown is the effect of mechanical damage on the mechanical properties. However, mechanical damage is very common in salvaged timber members, including holes, slots, milling pockets from joints, etc. as well as wear and tear, and accidental damage from assembly / dismantling (see e.g. Falk et al. 1999). Falk et al. (1999), report that damage affected the strength class in 30 % of the cases and led to downgrading by one class on average. Kenneth et al. (2001), Fridley et al. (2001) and Falk et al. (2001) analysed the effect of fastener holes on the bending capacity of reused timber members. They found that structural reliability is significantly affected by the hole location relative to the edge, similar to the grading criteria for knots. As fastener holes simply cut fibres, unlike knots where fibres nicely flow around, they affect the resistance approximately similarly as knots of twice the diameter.

Checks and cracks caused by moisture variations (primary drying) and possible part-time overloading might further limit the residual mechanical properties. Green et al. (2001) analysed the effect of heart checks on the bending properties of 6 inches by 8 inches Douglas-fir timbers. They found no influence on the Modulus of Elasticity (MOE) but a 15 % reduction of mean Modulus of Rupture (MOR). Their study did not address the effect sampling might have on the distribution of juvenile and mature timber which in turn would affect MOR and MOE.

Even earlier, Falk (1999) reported similar influences of checks on MOR and MOE. Nevertheless, checks and cracks are expected to have a significant influence on the tensile properties perpendicular to the grain as well as shear because of the reduced cross sections. Rammer (1999) and Falk et al. (2008) report high amounts of shear failures in their bending tests on reclaimed timber members. Specimens failing in shear showed significantly lower resistances than new timber (Rammer 1999); however, as will be discussed further below, the contributions from checks and cracks as well as duration of load (DoL) effects are not clear.

1 Effect of load history, moisture, and creep

Structural timber components might suffer from some biological degradation caused by insects and decay, as well as weathering. Before reusing structural timber for a specific project, conditioning to a common target moisture content (MC) might be necessary, as the components might come from different sites and might feature different MCs. Another important aspect are so-called long-term loading effects, which affect both the serviceability and ultimate limit states design and corresponding material properties. With increasing duration of loading, these effects lead to increasing deformations, i.e. creep, as well as reduced strength properties, i.e. duration of load (DoL) effect or static fatigue. In addition, the residual capacities to withstand cyclic loading (fatigue) may be of interest. In the current European timber design standard EN 1995-1-1 (2014; EC 5) these long-term loading effects are considered via the creep factor k_{def} and the modification factor k_{mod}; EN 1995-2 (2004) introduces the fatigue factor k_{fat}. For new timber products and constructions, the factors k_{def} and k_{mod} are tabulated depending on the service class, as a function of the expected MC, and the structural timber product. Yet, if and how these or similar factors are applicable to salvaged structural timber components is questionable. The main challenge is the unknown load history and consequently the degree of utilisation in serviceability and ultimate limit states for each individual piece of timber as precondition to reliably predict the residual mechanical capacity.

Recently, Cavalli et al. (2016) summarised past investigations on aged (small clear) wood and salvaged (structural) timber. With respect to the potential change in mechanical properties over time they differentiated between wood and timber degradation, the former being related to the state of conservation (durability), and latter describing the effects on mechanical properties due to long-term loading. According to their review, previous research found that the elastic properties (MOE in bending, tension, and compression parallel to the grain) are overall not significantly affected by long-term loading (Crews 2008; Crews & MacKenzie 2008; Falk et al. 2008; Nakajima & Murakami 2008; Falk et al. 1999; Rammer 1999).

In contrast, their findings regarding structural strength are much more diverse. This is in part owed to the fact that strength properties of reclaimed timber usually only be estimated as statistical values from past experience and present material properties. For structural timber, the MOR was found to decrease over time (see also Crews 2007, 2008; Crews & MacKenzie 2008; Falk et al. 2008; Nakajima & Murakami 2008; Falk et al. 1999; Rammer 1999). Based on their findings, Crews (2007) and Crews & MacKenzie (2008) outline the necessity to consider DoL effects in salvaged timber and proposed to reduce the MOR by 35 %, 50 % and 55 to 60 %, respectively, for members featuring load histories of short term / low magnitude loading, longer term / high magnitude loading, or unknown load history.

For compression parallel to the grain, the conclusions are less consistent; for example, Crews (2007) report on a comparable reduction in bending strength of members cut out from the compression and tension zone of larger beams. However, compression parallel to the grain is correlated with density which remains constant over time; see also Falk (1999) and Falk et al. (2000). There are also no clear results for the tensile strength parallel to the grain. With respect to the shear strength and in reference to Rammer (1999), the negative influence of splits and checks is highlighted; only half of the strength of new timber are reached. Yokoyama et al. (2009) conclude that well preserved wood remains safe under adequate conditions provided it is not loaded perpendicular to the grain. They also observed a significant embrittlement in old timber loaded in longitudinal or radial bending whereas MOE and MOR in longitudinal direction and MOE in radial direction remained constant but MOR in radial direction decreased.

The inconsistency of results in literature may be owed to underlying assumptions of the different studies. Generally, it is difficult to obtain good reference values for salvaged timber and comparable new timber of similar strength grades. In addition, the preparation of specimens from salvaged timber itself frequently involves machining of cross sections for structural testing. In consequence, only a limited or specific part of the original cross section is tested to failure. Furthermore, the number of destructive investigations on salvaged timber is rather small and often very specifically related to the object from which the material was salvaged. Cavalli et al. (2016) conclude for the effect of time on the mechanical properties that this is complex due to a number of interacting factors, such as (i) the state of conservation, (ii) the load history, (iii) the original grade / quality, and (iv) influences from damage.

To sum up, there are several experimental studies conducted on timber members reclaimed after being in service for years, decades or even centuries (e.g. Erhardt et al. 1996; Yokoyama et al. 2009). However, experimental findings vary with respect to elastic properties and significantly vary with respect to strength values when members were tested to failure in bending, tension, compression, and shear, both for small samples and samples in structural dimensions. With respect to strength, the outcomes indicate either a significant loss in magnitudes usually predicted from current DoL models (e.g. Rammer 1999; Crews 2008; Crews & MacKenzie 2008) or even slightly increasing capacities over time (e.g. Falk et al. 2000; Chini & Acquaye 2001). Fridley et al. (1996a,b, 1998) conducted extensive experimental, numerical and reliability based analyses. They conclude that the missing observation of DoL effects in their experiments is not the result of overdesigned structures but rather the effect of differences between real and modelled loading, i.e. the shape of load impulses. They recommend also to redirect experimental investigations on DoL from long-term low-stress testing to short-term high-stress testing.

2 Grading of recycled timber and design regulations

A remarkable development with respect to regulations for salvaged structural timber components is the Australian interim industry standard for recycled timber (Crews et al. 2008; with Crews & MacKenzie 2008 and Crews 2007 as background). This standard provides visual grading rules for salvaged hardwood components and guidelines for designers with respect to design properties, bolt holes and notches, connections as well as on DoL effects. In term of classification, the standard indicates that elastic properties of salvaged timber are similar to new timber whereas for strength properties a declassification by two grades is recommended. With respect to characteristic properties directly regulated for each grading class, this declassification corresponds to residual values of 60 to 65 % for bending strength, 50 to 65 % for tensile strength parallel to the grain, 60 to 65 % for compression strength parallel to the grain, and approximately 70 % for shear strength, depending on the grading class.

Overall, half to two-thirds of the characteristic strength properties assigned visually to new timber are considered for salvaged timber. Consequently, well-known relationships between strength and elastic properties are significantly different, i.e. shifted between new and salvaged timber components. In contrast to new timber, however, the long-term effects of loading on reused timber are reduced due to the unknown but successfully passed load history. This is done by assuming five months to 50 years of accumulated duration of loading. Based on the regressive relationship between load level and duration of loading, different load-duration modification factors are recommended as follows: $k_{\text{mod}} = 1.00$ for short-term loads

(< five days), k_{mod} = 0.98 for service loads up to five months, and k_{mod} = 0.90 for permanent loads with a duration of > five months.

This somewhat counteracts significantly reduced strength properties, since the Australian Timber Design Standard AS1720.1 (1997) recommends k_{mod} = 0.57 and EC 5 k_{mod} = 0.60 for permanent loads in service class one and two. For connections in salvaged timber the same k_{mod} factors are recommended together with 20 % lower strength properties of timber in conjunction with fasteners, e.g. withdrawal and embedment. This is justified by the fact that density remains unaffected by long-term loading effects, and density is the only timber property considered when describing the interaction between strength properties of fasteners and timber, i.e. embedment, withdrawal and head pull-through. However, it is not clear to the authors of this contribution why strength properties of fasteners should be less affected than all others in case of salvaged timber as the capacities of fasteners are a system property dominated by the local resistance of timber against compression, tensile and shear stresses in interaction with the fastener. This circumstance is also considered in the design of new timber structures where strength properties of the timber itself and those in interaction with fasteners are treated equally, i.e. the same k_{mod} factors apply. With respect to salvaged softwood timbers and in reference to Falk et al. (2008) similar regulations as for hardwood timber appear applicable.

3 Next steps

Currently, DoL effects for new timber are being discussed by the scientific as there is so far no consensus on the DoL models. Several physically based models are available; however, they still require calibration of input parameters based on test results which in turn are based on different test methods. It is also not completely clear to what extend current DoL models are able to represent the long-term behaviour of timber considering the high variability of timber properties with respect to the type and direction of loading. So far, there is also no consensus nor sufficient knowledge on the accumulation of load cycles in a static fatigue sense; analogies to dynamic, cyclic loading (fatigue) may provide a solution. Furthermore, the way test data are processed before DoL models are calibrated may have a significant influence on the outcome; methods like the equal-rank assumption need to be evaluated in more detail. Given that background, the aims of the envisaged study with focus on long-term loading effects on the mechanical properties of timber are to:

- expand and summarise the literature and re-evaluate existing data sets with respect to potential counteracting effects from partly deviating timber qualities in reference values compared to that of reclaimed timber;
- deepen and expand the knowledge on long-term loading effects on timber and joints in timber as preparation of a sound basis for possible regulations for salvaged timber;
- additionally, and exemplarily analyse long-term loading effects by means of reliability methods;
- develop proposals on how to regulate long-term loading effects for salvaged timber considering the following unknowns: load history and the number and duration of past service lives.

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Quantification and classification of salvaged timber components via Bayes updating

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1 Introduction

In order to ensure that salvaged structural timber (products and components) will be used widely again for structural, load bearing purposes a sufficient evaluation procedure is essential. Within such procedures, for example, it has to be ensured that timber with environmental degradation, or at least the degraded parts of the components, are excluded. Furthermore, the mechanical properties need to be quantified and classified accordingly. In principle every kind of available information, such as load history, various non-destructive and semi-destructive inspection methods, could be considered for such an evaluation. Therefore, the development and establishment of widely applicable standardized procedures are crucial.

Depending on the amount of the available material, its dimensions and the type of engineered wood product different procedures might be suitable. Considering e.g. the reuse of individual timber boards (or squared timber components) a detailed evaluation of the load history as well as time (and cost) intensive inspection methods might be disproportional to the economic gain. This needs to be considered although their general reuse potential might be high as such members may be reused directly for similar purposes in original or slightly reduced dimensions or serve as base material for structural timber products such as glued laminated timber (glulam; GLT) or cross laminated timber (CLT). In contrast, the reuse of the main structural components from a larger timber hall that will be demolished may be associated with sufficient value so that a detailed investigation becomes efficient, also from an economic perspective.

Missing regulations for the evaluation and reuse of load-bearing timber construction products according to their original purpose or as a base material for, for example, glulam and CLT, together with the conflict between the social mandate to use resources sustainably (and in the sense of a circular economy) and the constraints of economic considerations are seen as the main obstacles for the establishment of appropriate frameworks and possibilities. The aim of this contribution is to present a framework which is formulated on a mathematical sound basis, capable to handle in principle all possible types of information and an essential part in future regulations handling the reuse of salvaged timber.

2 Framework to estimate the mechanical properties of timber elements

The information for estimating mechanical properties of timber elements can be of very different nature; for example, it can origin from various building phases (e.g. the planned conditions) and different hierarchical levels of data collection, (e.g. (partly) known load history; results of various non-destructive and semi-destructive inspection methods (see e.g. Dietsch and Köhler 2010 for an overview of different inspection methods). Dependent on the investigation, however, different types of information are collected. They can be grouped as direct and indirect information, and as equality type and inequality type information (see Köhler 2006). For examples, see also Table 1.

A framework to consider different types of information is Bayes updating. For the procedure a prior information that can be quantified needs to be available. Such a prior information can be e.g. the planned conditions (if available) or an expert opinion; obviously the prior information is associated to uncertainties (see e.g. Rackwitz 1983 or Köhler 2006 for more information). Depending on the type of information different updating procedures are available, see e.g. Rackwitz (1983), Faber et al. (2000), Faber (2012), Fink and Kohler (2014). In Fink and Kohler (2015) a framework for the estimation of the strength properties of existing timber structures using Bayes updating is presented. Although the selected investigation methods might be different, the general principles are also valid for the estimation of mechanical properties of timber elements for the purpose of reuse.

3 Showcase – reusing glulam beams

There are several possibilities to reuse (or recycle) large-dimensional glulam beams. The ideal case might be reusing without any further processing. Obviously, the options to reuse large-dimensional timber components are limited because they are usually designed for specific structures and use. Considering smaller geometrical adoptions (planning, end cutting, etc.), the scope of possible applications will increase, however it might be still limited. Anyhow, from a structural engineering perspective, a reliable estimation of the mechanical properties would be needed. Table 1 shows a compilation of information from non-destructive inspections and evaluations, classified according to the type of information for the estimation of the strength properties.

Table 1. Examples of different types of information for the estimation of the strength properties of glulam beams based on non-destructive inspections and evaluations.

Direct & equality type information
- Destructive testing is the only possibility to get direct and equality type information. For the quantification of an individual structural component this is not possible (as the component is damaged after testing). However, for the estimation of the strength properties of a set of glulam beams (assuming they belong e.g. to the same strength class, fabricated by the same producer, etc.) destructive tests performed on selected samples could be used to estimate the strength properties of the entire sample.
Direct & inequality type information
- Load history: the bending strength of the beam in the past was at least as high as the bending stresses caused by loadings at that time; because of duration of load (static fatigue) effects in timber and possible additional damage in conjunction with high loading meanwhile the bending strength might be lower. At the same time, the information of survival together with the duration of load effects can also be used to exclude low realizations of the basic population (Kohler 2014). - Proof loading: the bending strength of the beam is at least equal to the bending stresses from proof loading. As before also here possible damage needs to be considered.
Indirect & equality type information
- Stress waves or ultrasonic runtime: e.g. estimation of the strength properties based on the dynamic modules of elasticity using correlation models. - Deformation measurement: e.g. estimation of the strength properties based on the static modules of elasticity back calculated from deformation measurements from well-defined static systems and loads by means of correlation models.
Indirect & inequality type information
- Status inspections (e.g. visual inspection, environmental conditions, moisture content, cracks, endoscopy); please note: such inspections can be very useful for the identification of environmental degradation, however, for the purpose of a quantitative assessment they are of minor importance and thus not further considered here.

It should be noted that for reusing entire glulam beams several aspects, besides the estimation of the mechanical properties, need to be considered. Examples are CE marking and material storage. An alternative approach could be the further processing into smaller components (e.g. glued solid timber elements with standardized dimensions) or components with common cross sections that are acting as base material for glued products such as glulam and CLT for which thin resawn products of such glulam members might be used as single layers. The potential to reuse small-dimensional components without changing their original cross sections might be easier in particular when the cross-sectional dimensions are somehow standardized. This is in particular true for glulam beams featuring a homogeneous layup whereas the possibilities are limited in cases of heterogeneously built up glulam beams. Regarding the quantitative assessment the same NDT methods as presented in Table 1 are suitable, however, especially regarding the destructive tests a significantly larger sample might be possible. Furthermore, existing strength grading methods (both visual and machine grading) can be applied, and the results can be used to enhance the estimation.

4 Conclusion and outlook

Reusing salvaged timber elements can result in environmental and economic benefits. For example, addressing global warming, extending the life-time of structural timber products directly impacts the carbon storage capacity of timber and opens up possibilities to use new timber for others than structural purposes. One challenge therefore is the quantification of the mechanical properties, in particular of strength values. In this note the estimation of the mechanical properties by using Bayes updating is shortly introduced. In principle the same approach can be also extended for the evaluation of timber connections or even entire structural systems. This could also be potentially used for the evaluation of existing buildings, for example for the sake of adoptions or renovations.

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Design for disassembly - learning from traditional and contemporary building techniques - case studies

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1 Introduction

The concept of performing a design process while taking into consideration the future disassembly and the possibility of further using the structural elements after the end of usage of the building is a up-to-date research topic due to the fact that contemporary constructions are responsible for a high use of various materials and a significant amount of the generated waste. Still, the concept of designing a building while thinking about a future disassembly is not a new concept. It is a principle that has been common since neolithic times, especially in the case of timber structures (Crowther, 1999). Tents or other similar shelters were built using timber structural elements, simple joints, and perishable exterior materials, which made their disassembly easy. The same can be observed later on, in the case of roof structures where timber elements were reused from one building to another (Keller, 2020). This was only possible due to the use of traditionally crafted timber joints, with steel of timber pegs, which allowed easy disassembly and reassembly in the new place.

2 Principles and practices

The concept is defined by a set of principles which make the whole process of repair, reuse, upgrade, and even disassembly of a building during various interventions or after its end of life, while still highly complex, easier to follow (Bertin et al., 2022; Crowther, 2018; Tleuken et al., 2022). The main principles are as follows:

- The use of materials that can be reused, in a different context, or recycled makes wood a suitable material for buildings that are designed while also considering future disassembly
- Use of joints that are visible and easy to reach so that proper maintenance is possible and disassembly can be performed without affecting the structural elements.
- The use of connections that can be easily disassembled. In the case of timber structures, traditionally crafted joints using timber or steel fasteners have proven to be efficient over time.
- The use of few/similar types of connections, structural elements and modules in order to make the assembly and disassembly of the building easy and less time consuming
- Designing structural elements that can easily be transported on site, or from one site to another

3 Traditional building techniques

To better understand the concept of circular economy and the principles of design for assembly as a first step, the knowledge of design and construction during major historic periods was analysed. The construction history shows that the Dfd principles, which are now a up-to-date research topic, were already used for most of the historic timber structures (Crowther, 1999). An interest towards following principles was observed:

- Use of timber elements with dimensions which can make them easy to be handled and development of connection joints which allow the increase of their length

- Clear assembly rules that make disassembly easy
- Clearly numbered timber elements to identify their position during the assembly, and to be able to further reuse the components after the end of life of the structure.
- Clear design rules using a small number of timber element cross sections and repetitive joints, in order to encourage a future reuse of the structural components
- Possibility of replacing certain components of the structure if they suffer damages due to the use of traditionally crafted timber joints with wooden and steel fasteners

These principles were also observed during comprehensive studies conducted on historic timber roof structures in Europe(Keller & Mosoarca, 2017; Mosoarca & Keller, 2018). Roof structures represent one of the most complex databases concerning traditional building techniques and detailing, a database that can be used as inspiration for contemporary timber buildings, since the construction techniques have proven their efficiency over time. The study has shown that these structures were designed and built with respect to a series of strict geometric principles defining the cross section of the timber elements and their position. The structures have a repetitive pattern, being altered only to comply with certain architectural/aesthetical requirements. More than this, up until the beginning of the 20th century the structures were marked with a carpenter mark, in order to be able to identify the craftsman involved in the construction process, and numbering signs, placed on each timber element, used to identify matching structural elements and be able to join them in the correct place.

The connection between the linear timber elements was made using a great variety of joints, which can be divided into four main categories: tenon and mortise joints, notch joints, lap joints, and scarf joints. All these joints were additionally connected by using wooden pegs or later on in the twentieth century by steel pegs.

The reuse of timber roof structures can sometimes be observed in the case of buildings that suffered damage or changes. In most cases a series of mortise cavities or signs of previous joints can be observed in the area of the main structural elements, which is a clear proof that the structures were disassembled and adapted to a new context and comply with the new structural requirements (Keller & Mosoarca, 2017).

The same was observed in the case of traditional log buildings, both religious and residential (Isopescu & Stoian, 2019) throughout the world, which were built taking into account future necessary interventions/repairs or changes and are therefore already designed for disassembly. The joints used were also made to facilitate the disassembly of the building and its reconstruction in a new place if necessary.

Both cases highlight not only the possibility of reusing timber structural elements, but also the need to clearly understand the dependency between elements, both structural and nonstructural, and how each layer of the building can be adapted or reused without affecting the others. Only in this way, all the components, load-bearing and nonload-bearing materials of a building can be disassembled while preserving the service and aesthetic qualities with minimal alterations.

4 Contemporary building techniques

A series of studies have also been performed on the potential of using the design principles for disassembly in new timber structures. All of them show that the concept has to be considered from the early design phases of a building, significantly influencing not only the architectural layout of a building and its load bearing structure but also all the other professionals involved in the design process. Still, they highlight that despite the effort, this type of approach can be a real alternative to current demolition practices (Rios et al., 2015).

One of the most recent studies on this topic (Piccardo & Hughes, 2022) consists of a comprehensive study on a series of case studies. Case studies, identified in a list of reviewed articles, were designed considering the reuse of timber elements, some after the end of the building's useful life, and other by reusing salvaged structural elements. During the study, all case studies were analyzed on the basis of a series of criteria.

- Joint configuration and its ability to be disassembled after the end of life of the building
- Relation dependency refers to the effect the disassembly of certain elements will have on the integrity of other structural and nonstructural elements. This feature greatly influences the service life of reused structural elements (Galle et al., 2017; Vandervaeren et al., 2022)
- Level of prefabrication referring to structural components or modular elements that were designed and manufactured without considering their subsequent disassembly
- Recovery of salvaged wood and adaptable building layout, depending both on the considered construction system and its ability to also include salvaged timber elements.

Studies highlight that if the Design for Disassembly concept is taken into consideration, important decisions have to be taken from the first design phases, so that the structural or nonstructural elements are manufactured taking all these principles into consideration so they can be adapted over time.

Therefore, starting from these principles and all the principles characteristic for the Design for Disassembly concept, a series of additional case studies (Table 1, Table 2) in order to bring forward how the concept is approached by different professionals.

Case studies in the field of design for future disassembly are surprisingly few taking into consideration the history of timber structures and their adaptability and even fewer that use only timber. Still, a special interest was observed for demountable structures in the case of the modular structures developed for the Solar Decathlon competition (EFdeN, 2022; Roofkit, 2022), where all the DfD principles are identifiable since the developed structures have to be easy to build, transport, and most of all easy assembled and disassembled, while taking into consideration current standards and norms like energy efficiency or acoustics. More than this, many of the developed structures are modular, offering the possibility of adapting the building during its use. They represent therefore an important base for future studies concerning DfD.

Table 1: Case study analysis – basic data

Case study	Country	Year of construction	Function	Height	Structural system	Structural material
Woodcube (ArchDaily, 2013)	Germany	2013	Residential	5 stories	Reinforced concrete core Solid cross-layered panels	Timber and Concrete
Nest We Grow (ArchDaily, 2015)	Japan	2014	Public	4 stories	Rammed-earth walls and timber column beam	Earth and Composite Timber
VATRA Prototype(EFdeN, 2022)	Romania	Concept (2021-2022)	Residential	up to 6 stories;	Panels + timber columns	Timber
RoofKIT(Roofkit, 2022)	Germany	Concept (2021-2022)	Residential	Up to 3 stories	Beam and column	Timber

Table 2: Case study analysis – DfD related principles

Case Study	Joint Type / Material	Joint dissasembly	Possibility of considering a circular system	Dependency between elements	Prefabrication	Dimension of elements
Woodcube (ArchDaily, 2013)	Wood plugs	yes	yes	no	Yes, pre-fabricated walls and slab panels	medium
Nest We Grow (ArchDaily, 2015)	Traditional inspired + Steel	yes	yes	no	yes	small - linear elements
VATRA prototype (EFdeN, 2022)	Steel	yes	yes	no	yes - modular	small - panels
RoofKIT(Roofkit, 2022)	Reversible - No glue or sealants	yes	yes	no	Yes – prefabricated structural units	

5 Conclusions

This paper comprises the main design principles identified after the analysis of the literature on DfD. The study focuses on historic timber structures that were built using traditional building techniques and reversible joints and have therefore become suitable for disassembling after the end of life of the building but also on contemporary buildings, already designed considering their future disassembly. Based on the analysed paper and identified case studies, it can be observed that the topic is currently insufficiently approach despite the EU recommendations.

At the same time, despite the suggested design guidelines, the principles are insufficiently defined and leave room for future interpretation, standards and norms are not suitable to encourage the use and reuse of structural and nonstructural elements. This can be observed in all the analysed case studies which still highlight the struggle of identifying suitable solutions. Therefore, it is of utmost importance, by focusing on circular strategies for timber structures, to further develop DfD principles and include them in contemporary design standards. This has to be done through the involvement of all types of professionals from the early design stages to be able to coordinate decisions and find proper solutions while respecting the Dfd principles.

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Barriers to design for disassembly and reuse of timber and lifecycle potential of service time expansion

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1 Obstacles to Design for Disassembly and Reuse (DfDR) of Timber

Although not extensive, the literature on the design for disassembly and reuse (DfDR) of timber increased quickly in the last couple of decades (Thormark, 2001; Crowther, 2005; Gorgolewski, 2008; Hradil, 2014; Diyamandoglu & Fortuna, 2015; Huuhka, 2018; Cristescu et al., 2021; Sandin et al., 2022; Piccardo & Hughes, 2022). Nevertheless, despite the increasing body of research on the subject, Cristescu et al. (2021) point out that for the established knowledge to become valid and guide decision-making in practice, a more detailed set of principles is lacking, linking appropriate strategies to each stage of design or construction.

In that regard, Cristescu et al. (2021) identified three main obstacles hindering a more widespread DfDR of structural timber. (1) Building regulations present the first hindrance, as the same procedure for grading new timber should be employed to assess the strength of reclaimed components. Without this step, even perfectly reusable and high-added-value load-bearing components must be downgraded and applied for non-structural purposes (Hradil et al. 2014). (2) The second challenge refers to building demolition processes and has a fundamental and evident role in the recovery of quality material for reuse. Yet, demolition methods are rarely considered in the design phases and construction of buildings, often driven by economics and time constraints. That, in turn, leads to demolition practices that rely on heavy equipment, damaging otherwise good material, and thus hindering its reuse or recycling (Chiara and Hughes, 2022). As an example of the importance of demolition methods, Diyamandogly (2015) studied the potential for the reuse of light wood framing systems and stated that around 25% of wood-based materials could be reused but only when soft-stripped. (3) Finally, architectural obstacles provide the third barrier to timber DfDR in construction. Beyond the hindrance of grading and demolition methods above, the simply high variability of pieces in terms of length, section, and looks creates a substantial challenge related to dimensional coordination, thus generating a higher design burden. Hence, designers sometimes perceive DfDR as if they are taking increased risks by specifying components with less predictable characteristics (Gorgolewski, 2018). Moreover, the second obstacle of demolition is also defined during the design process, leading Hradil et al. (2014) to conclude the greatest impact on a building material re-usability derives from its design stage.

Likewise, after developing a qualitative case study of five buildings, Sandin et al. (2022) found design aspects such as reversibility of connections, easy access to components, and standardization of parts to be essential principles for an increased DfDR of timber. Similarly, a recent case study research by Chiara and Hughes (2022) corroborates the idea that designers play a substantial role in enhancing the reuse of wood. They concluded that end-of-life management is often not part of the design process, frequently resulting in fixings and joints that are difficult to disassemble. The authors then propose dividing DfR strategies into upstream and downstream groups of activities to tackle the full scope of DfR strategies (Chiara and Hughes, 2022). Upstream activities are developed in the design phase to facilitate future timber reuse, especially in the maintenance and end-of-life phases. Downstream activities concern the salvaging of wood from buildings during renovation, deconstruction, or demolition, followed by their (re)use in a new building.

However, Chiara and Hughes (2022) warn that both upstream and downstream strategies implementation are more complex than conventional wood use as it entails specific expertise concerning the material-efficiency design of buildings. As the implementation of strategies to recirculate wood in constructions is relatively recent, expertise is still lacking, and standard procedures are fragmented. (Chiara and Hughes, 2022). In a study evaluating the significance of architectural design for reclaimed timber reuse, Huuhka (2018) found the inherent material properties to affect the whole spectrum of architectural design. Due to the lack of realized projects reusing timber in a downstream direction, Huuhka (2018) developed a theoretical design exercise with students leading to 10 relevant practical design guidelines. The study by Huuhka (2018) is cited in the recent literature, thus achieving a real impact in the field and portraying one path where educational activities can contribute to improvements in real-life practice.

2 Lifecyle benefits of DfDR and DfA (Design for Adaptability)

The literature on the environmental impact of the construction sector consistently favors wood-based building materials as a means to reduce GHG emissions due to the biogenic carbon content in wood (Gustavsson & Sathre, 2006; Robertson et al., 2012). However, studies also showed the uncertainty of biogenic carbon benefits as it varies depending on a specific time scale and adequate end-of-life (EoL) scenario for wood-based products (Börjesson & Gustavsson, 2000; Gustavsson & Sathre, 2006). Hence, a considerable number of more recent studies on the LCA of taller timber buildings also started to tackle the time dimension and its influence on environmental performance (Pittau, 2018) (Head, 2020) (Zieger, 2020) (Morris, 2021) (Resch, 2021) (Göswein, 2021) (Robati, 2022). The dynamic LCA studies quantify the extended effects of biogenic carbon storage in fiber-based materials aiming for more accurate assessments of its impacts on buildings and materials. Those studies conclude that considering an expanded time horizon, sometimes up to 500 years (Zieger, 2020), is beneficial to fiber-based products (Zieger, 2020) (Resch, 2021). The results also show that when the timing is considered, the faster the growth rate of fiber-based materials, the more beneficial it is in the short term, which gives an advantage to straw, hemp, and cork over wood (Pittau, 2018), although the differences between fast- and slow-growing biomaterials level out in the long-term (200 years horizon) (Göswein, 2021). In the same line, recent papers started to stress the relevance of the end-of-life scenario and further potential for mitigation of extending the lifespan of buildings and materials through strategies such as design for adaptability, disassembly, and reuse to increase the time-related benefits of wood-based materials (Morris, 2021) (Resch, 2021) (Kröhnert, 2022) (Robati, 2002). Likewise, Passarelli (Passarelli, 2018; Passarelli, 2019) reiterated the critical role of EoL and demonstrated we can improve the environmental benefits of wood construction by reclaiming and reusing wood-based materials instead of combusting or composting them. Nevertheless, the former study uncovered two critical unforeseen practical challenges of reuse. Designing from reclaimed materials led to an increased design burden and high material loss from remanufacturing as elements were not optimized for reuse. The results of the LCA review, therefore, reinforce the findings about the main barrier for a more widespread implementation of DfDR.

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SG Repairability and maintenance

Repairability and maintenance of timber buildings – need for future timber buildings

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1 Introduction

The topics of circularity, adaptability, repairability, and maintenance are currently broadly discussed in architectural and structural research and also in the focus of this COST Action. All of them aim at reducing the sustainability impact of buildings.

Maintaining the existing building stock for its planned service life and beyond is the most efficient way to preserve the materials' grey energy within the building stock and prevent unnecessary consumption of new resources and energy for their replacement. In addition, maintenance of existing timber buildings ensures continuous carbon storage, which contributes to the transition to resource-efficient buildings to meet the climate challenge and achieve a sustainable society.

However, the relevant international standards lack effective design guidance to quantify and verify the performance of existing timber structures. Design guidance and recommendations for structure maintenance, assessment, and repair need to be developed and disseminated to practice. That way the sustainable use of the resources in buildings will be ensured.

Repair and maintenance of timber structures has been in the focus of many research projects and programs in the past. Within this COST Action CA20139 the focus is set on modern taller timber buildings, in contrast to much previous research on historic buildings (such as (ICOMOS 2008)).

2 Terminology

2.1 Maintenance

According to (BSI 1984) “Maintenance is the combination of the technical and associated administrative actions intended to retain an item or system in, or restore it to, the state in which it can perform its required function”.

2.2 Repair and Reinforcement

An inspection, structural analysis, and verification may conclude that repair is necessary to restore the damaged or deteriorated structure to its original condition.

Reinforcement is according to (SIA 2011) a measure to improve the load-bearing resistance and serviceability of a structure or component. (Branco et al. 2021) gives a recent overview of different reinforcement methods.

3 Demands for maintenance and repair

Examples of aspects that may require the need for adaptability of structures can be summarised as follows:

- Changing user demands on a building and structure
- Changing structural demands

- Repair of damages
- Upgrading due to increased regulatory demands (e.g. energy saving requirements)

Addressing these aspects already during the design stages of a building will strengthen the confidence in timber buildings and support the wider use of timber in buildings. In a research project carried out in Sweden in 2019 (Jockwer et al. 2020), a high interest of building stakeholders & insurance companies was identified in interviews regarding solutions to mitigate the effects of fire and water damages. Property owners showed a high interest in maintaining the value of their property through repair and maintenance.

4 Examples of need for repairability and maintenance

4.1 Critical details

Due to its natural composition wood can show biological decay when exposed to unfairoable environmental conditions over longer time. Maintaining and ensuring the optimal environmental conditions for the wooden members can enable a maximum service life of a structure. Some examples of critical details that may require repair are:

- Problems with details at e.g. balconies etc
- Water damage on a floor due to leakage
- Damage of an interior wall due to leakage of a kitchen pipes
- Moisture damage behind a shower unit due to crack in the sealing
- General problem with flat roofs
- Local fire damage in parts of a building

4.2 Challenges regarding repairability

The need for repair of damages often raises a variety of challenges:

- How can damaged elements be repaired?
- How can elements be disassembled and re-connected
- Conflicts with different users in a larger timber building
    - Exchange of walls or floors affects multiple parties
- Large elements
    - How to exchange an entire floor or wall?
    - How do you get an entire floor or wall in place (e.g. center of a building)

Robustness is most often referred to in the context of avoiding disproportional collapse of structures. However, more general robustness should limit the extent of disproportional consequences of an event. Hence, robustness frameworks can also be applied to non-structural events and damages that might for example cause disproportional costs or impacts. Having this in mind the possibility for an easy repair should be considered already in the planning phase of the building. Easy detailing, which allows for disconnection, exchange, and replacement can facilitate the repairability of a structure considerably. This includes also the separation of members with different function in a structures, such as envelope elements in the façade and the main loadbearing structure.

5 Importance of enhanced maintenance

General

- Implementation of NDT and updating in the maintenance and repair process
- Risk based maintenance and repair for optimisation of intervals and actions

Some specific aspects

- Central and accessible installations
- Monitoring of structural details (e.g. post-tensioning)
- Accessibility of neuralgic members and details (e.g. major joints, structural systems, post-tensioning)
- Areal moisture monitoring

6 Repair and maintenance in previous research programs, projects, and existing guidelines

6.1 COST Action FP1101

COST Action FP1101 “Assessment, reinforcement and monitoring of timber structures” had the objective to increase the acceptance of timber in the design of new structures and in the repair of existing structures by developing and disseminating methods to assess, reinforce and monitor them (Harte and Dietsch 2015).

The COST Action was structured into three working groups: Working Group 1: Assessment of timber structures, Working Group 2: Reinforcement of timber structures, Working Group 3: Monitoring of timber structures.

6.2 Guidelines

6.2.1 Standard SIA 269

The Swiss Standard series SIA 269 covers the basis for examination and interventions for existing structures and the subsequent series covers specific rules for actions on existing structures and for the different building materials with timber being covered in Standard SIA 269/5. An introduction into the standard series is given by (Brühwiler et al. 2012). It is pointed out that interventions (operational and/or constructional) need to be optimised and the issue of proportionality of an intervention needs to be addressed in this context. Some aspects related to the maintenance and rehabilitation of timber structures are pointed out by (Steiger 2010).

6.2.2 CEN/TS 17440

CEN/TS 17440 (CEN 2020) is a technical specification documents by CEN on “Assessment and retrofitting of existing structures” that was published in 2020. Similar to Standard SIA 269 it covers the basis of design. It is specified in its introduction that the rules in the Eurocodes (EN 1990 and following) are primarily intended for the design of new structures. CEN/TS 17440 is intended to supply additional or amended provisions in order to apply the principles of EN 1990 also to existing structures. More specific application rules focussing on timber structures are still missing on European level.

7 Implementation and need for further development

Considering the repair of a building holistically a strategy against unforeseen events and consequences already in the design will help to ensure the long-lasting performance, efficiency, and sustainability of timber buildings.

In order to facilitate repairability and maintenance of buildings in practice it is necessary to work towards specific education of engineers and architects, authorities, other stakeholders such as insurance companies and develop adequate guidance documents. In addition, robust details need to be developed in collaboration with practitioners and manufactures and established in the market and industry.

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(P)Re-paring taller wooden buildings: Building enclosure detailing importance in durability of non-transparent envelope

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Timber structures are prone to damage due to nature of the wood as an orthotropic material with properties different in different sides of the element (timber is strong along the fibres, but very weak across them), also, it creeps with time, which can be critical in heavily loaded structures like tall timber building (Voulpiotis at al. 2021). Complex phisical and structural properties in timber structures leads to neccessity to design these structures through details by taking into consideration durability, maintainability, fire safety regulations, building physics and indoor air quality parameters. Besides that separate parts in the building play different roles, the composition and interaction between these is even more important.

This paper aims to show how the adequate design of details, layers, joints, and other elements affects the need for restoration and repairs. Inadequate approach to the selection of materials, poor joints or penetration between different elements are the primary factors influencing later problems in the use of buildings, thus necessity for the repairs. They can lead to envelope disassemble, appearance of moisture, mould growth, discoloration, falling out of segments or connecting elements from the envelope etc. A special reflection will also be made on the relationship of well-resolved details (mainly non-structural) to internal comfort in terms of the thermal characteristics of the space as well as the quality of the living space in general.

Indoor Environmental Quality (IEQ) of buildings include aspects of the built environment that affect occupant health and well-being, and commonly includes factors such as indoor air quality, thermal comfort, visual comfort and acoustic comfort (Arif et al. 2016). All these parameters are affected by the building envelope performance as a boundary between the indoor space, and user behaviour and the external influences of the environment.

For tall timber structures, the design of the building envelope damage due to long-term exposure to water and short-term and long-term shrinkage that can occur as a result of structural loads or changes in moisture content (Green and Taggart 2017) since timber is hygroscopic material which degrades significantly when it remains wet for a long time (Voulpiotis at al. 2021).

1 Building envelope components overview with specific role in physical performance of the envelope

According to Voulpiotis et al. (2021) wood is shown as a material with numerous benefits, however, it also comes with great challenges that need to be taken in consideration such as: sensitivity to moisture, light weight, othotrophic properties, low stiffness, brittleness, system, size and time efects that influence on overall perormance of timber structures. The above properties make the design of a timber building everything but straightforward, particularly at larger scales. The most complex part of the building in terms of building physics is certainly the envelope, which affects both physical properties and quality of life of the tenants.

In order to design structure which is both structurally robust and cost-optimal, integral design principles include thermal specialists which track suitable conditions under environmental changes, building physicists which are researching material mutual behaviour within complex envelope structures such as moisture control and thermal conductivity, architects capable for managing complex details and detailed designs, HVAC engineers, structural engineers and contractors, shall be involved in the panels' design phase (Gajić et al. 2020).

It is necessary to look at what makes up one envelope, after which the combinations of materials and the places where conflicts occur should be examined in order to provide high quality details that will eliminate the need for major renovation projects. According to (Green and Taggart 2017) main envelope components are listed below:

- **Thermal insulation** is only one of many components that make up the building envelope, although is the most important in terms of energy conservation and thermal comfort. Certain thermal insulations have high fire resistance (rock wool), high level of water vapor diffusion resistance (vacuum insulation panels), humidity control and noise reduction. All insulation materials have their own strengths and weakness, and these should be evaluated primarily against the design, durability, cost-effectiveness, and environmental impact criteria.
- **Vapor barriers** are used to control the diffusion of water vapor through the building envelope and prevent vapor from condensing on colder surfaces as it migrates through the assembly. Vapor barriers are most important in cold climates in which the need for heating predominates, as well as in the buildings with different heat zones where heat flows are significant (Čvoro and Peulić 2019). Barriers are installed on the interior side of the insulation in most wall and roof assemblies, and typically consist of a coating, a membrane, boards or other rigid materials. In both thermal insulation and vapour barriers some other influential parameters can disrupt these orders, etc. buildings under protections, when some contemporary materials and details need to be consulted; in either way these materials need to have as low coefficient of thermal conductance, high level of fire resistance, and ability for vapour diffusion conduction. (Gajic et Al. 2019)
- **Air barriers** can be used anywhere in a building envelope assembly to stop the movement of air into or out the conditioned space and control heat losses or gains and moisture transfer. Air barriers can be in form of wraps, self-adhered membranes, spray-applied materials, rigid sheets, or any other layer that prevents the passage of air. The key concern is that it must be continuous with lapped joints if it is film or membrane, sealed joints if it is of panel construction – and all penetrations (pipes, ducts, windows and doors) must also be sealed.
- **Finishing layer, or sometimes called water-resistive barrier,** is the one mostly exposed to the environment. It is most prone to damage both from the inside and outside. In case of wooden structures most often it is about light materials that can be easily replaced. Mostly, this is about mechanical types of connections, although the use of construction adhesives is not uncommon either, which only apparently accelerates construction, but in fact are dependent on the temperature and humidity on the construction site, which cannot be controlled. It is positioned within the wall assembly to protect vulnerable components from damage caused by water penetrating the assembly from the outside. The first line of defence is often a rainscreen cladding system, in which the cladding is fastened to vertical battens mounted on the exterior face of the wall assembly. Aging of materials, especially wood, should be seen as a natural feature and the details should be adapted to that feature. Here, the most important features are actually the type of wood, the way it is processed, as well as the

layers that occur in the background, considering that the biggest problem can be caused by simultaneous atmospheric influences from the outside and water vapor from the inside.

Besides above mentioned, there is additional one which can contribute to overall durability:

- **Installation systems** – Although they do not belong to the envelope layers, the installations are located within the walls, both internal and external. Therefore, it is necessary to classify them as potential elements of conflict that lead to the destruction of the internal structure of the wall and actually represent one of the most common problems of the appearance of moisture, mould, material deformation, and therefore the need to, very often, replace the entire wall. Here, special attention should be paid to water and sewage pipes, which, in addition to damaging the integrity of the wall, conduct matter in a liquid state and at different temperatures, whose leakage can damage severely integrity of the layers, walls or even whole building in case of late detection and untimely reaction.

2 Thermal performance and moisture flows treatment

In order to be durable and to avoid necessity for often repairs a building detailing has to be made right. It is necessary to ensure several things while making detail designs and follow these on construction sites. Firstly, it is necessary to control that presence of moisture in building materials is on adequate level during transportation, installation and usage phase. The moisture content of the wood components should not exceed 19%. As the enclosure consists from multiple layers with specific roles in building physics properties, problems can occur on the joints, overlaps, gaps and penetrations. Thus, it is crucial to ensure air-tightness of the building – thus install details with membrane overlaps and correct array of the layers and avoid thermal bridges on connections. Thermal performance of a building depends not only on the continuity of the air barrier, but on the integrity of the insulation. In the solid portions of walls or roofs, thermally conductive components should not penetrate the full depth of insulation as they will create thermal bridges, where heat loss or condensation will occur. Predict continuous thermal insulation on opaque part of the envelope including balconies, overhangs etc. Occasionally, penetrations are unavoidable, so each has to be designed carefully to ensure continuity of other materials. Common practice is that balcony structures do not penetrate buildings' envelope - they are independent structures suspended by rods that are attached directly to the external wall structure (but do not penetrate the insulation). Windows and door frames that penetrate the full depth of the exterior wall assembly must be thermally broken with insulating material separating the various parts of the frame or constructed from non-conductive material such as wood or fiberglass. Predict installation shafts for ease of maintenance and ensure that sewage and water pipes are reachable and well-connected during installation.

3 Problems detection

Non-destructive methods make it possible to see the problem without revealing the structure. This significantly reduces the time it takes to find defects and reduces the amount of waste generated as a result of renovation. Thermal imaging can show different wall temperatures, which can be associated with the appearance of moisture as well as cracked pipes or dew on metal pipes. Micro cameras allow detailed inspection of the pipes, so the cracks can found precisely and later logistics can be developed on which part of pipe needs to be replaced. There are many sources of building moisture, including humidity, condensation, pipe leaks, rain and snow, and even people and animals breathing. A thermal imaging camera cannot "see" moisture in walls, but it can detect subtle temperature differences and patterns that reveal the existence of water. (Flir 2019)

4 Conclusion

The work presented physical properties of the envelope with overview on specific role of each material in the ensemble. The complexity of the design including numerous actors need to provide an integral thinking on timber structures in order to reduce the demand for the repairs and avoid collisions and material decay. Further work can go with analysis of good case study examples with focus on three points: layering of the facade, installation systems inside the wall and protective coverings.

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Horizontal topics

Computational methods supporting design for robustness, reuse and repair

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1 Introduction

Addressing robustness, adaptability, disassembly, reuse and repairability in the design of taller timber buildings as strategies towards more sustainable buildings requires the integration of a large number of divers, interacting and often contradicting design parameters into the design process of buildings and their construction elements. Complex design is driven by a variety of relevant performance parameters creating a solution space beyond the regular expectable design space. Solutions where the various design aspects accumulate to an effective, efficient construction will be rare peaks in large and cliffy solution spaces characterised by a high level of customisation and differentiation. Specialised and differentiated construction elements require customised fabrication methods with a high level of precision. Computational processes from design to fabrication and robotic production provide an efficient and seamless materialisation of highly customised construction members. Robotic assembly complete the digitised and computational workflow from early design stages to the actual erection of the building.

Replacement or relocation of elements require robust information about the element and its properties. Digital models of the element and the respective constructive environment are indispensable to enable competent decisions on potential reuse of parts.

Numerical simulations based on digital models are essential to evaluate the quality of a design solution. Combining simulations with parametric models and optimisation engines provides a design environment where form could be found on a data informed basis aspiring to fulfil relevant objectified design goals.

Robustness, reusability and repairability are major contributors to sustainability not only but also for taller timber buildings. Computational methods are concerned with the robotic or digitalised fabrication of constructions and its elements, the assembly of discrete elements, with the topological and geometrical description of construction elements and their relations as well as with the description and integration of material properties into these processes.

This is a collection of contemporary techniques, methods, case studies and concepts within the realm of computational methods which are directly or indirectly addressing robustness, reusability or repairability. The report investigates the pathways of academic research and the contemporary application thereof in practice.

2 Computational Design

2.1 Multi objective optimisation

The design of sustainable taller timber buildings is a challenging task demanding multiple design parameters to be considered within the solutions. The integration of material or fabrication related aspects into the design process culminate into a complex design process. Considering the robustness of these buildings and their elements, their repairability or their potential reuse after the end of the building's life, add to the complexity.

Multi-objective optimisation methods provide simulation-based results to inform design decisions in complex design scenarios to address building performance and other design criteria. Transformation of the abstract design goals into parametric description of the geometry and comparable evaluation is key to successful optimisation algorithms. Evolutionary genetic algorithms are robust and therefore generally suitable for design problems. (Spaeth, 2016) Due to contradicting and overlapping design criteria optimisation procedures typically provide a multitude of comparably good solutions in a pareto front rather than a single optimal solution.

The adoption of computational tools is highly dependent on their accessibility which correlates directly with the necessary expert knowledge and level of necessary computational accomplishment. Visual user interfaces and graphical illustration of results increase the acceptance of such tools as within i.e. Rhino Grasshopper and respective plugins. (D'Agostino et al., 2021) (Joyner et al., 2022).

2.2 Generative evolutionary algorithms

Simulations used as evaluation systems in evolutionary design systems demonstrate the robustness of the evolutionary algorithm in ill-defined design environments and the ability to generate form on the basis of given output criteria. Generating form with target design parameter is viable as a proposed design system generating form on the basis of acoustic and geometric target criteria proved in concept. (Spaeth, 2016) Although demonstrated on acoustics and geometric criteria as design drivers the complexity and nature of simulations could be potentially transposed into the realm of timber constructions.

2.3 Neuronal Networks

Neuronal Networks (NN) a section within in the realm of Artificial intelligence (AI) artificially remodels the communicative system of the neuronal activity in brains. Neuronal Networks can be trained to make informed decisions on specified problems. NNs can be trained with data from simulations which they learn from. After training the NNs are capable of applying their acquired knowledge onto new, unknown situations. Training data of parameterised school buildings in correlation with simulated daylight metrics enable the NN to predict daylight situation for new constellations within the school building without the need of time-consuming simulations. (Lorenz et al., 2018) The implementation of design solutions proposed by a Neuronal Network on a parameterised geometry model considering complex daylight predictions, indicates a potential use in a design environment for timber constructions.

3 Computational Fabrication

3.1 Robotic fabrication

A digitalised workflow with digitalised planning models, to an explicit digitalised representation of construction elements enable the direct and seamless robotic fabrication of the respective elements. Robotic fabrication enables individualised mass customisation within differentiated design solutions at reasonable costs. The robotic customised fabrication of the differentiated joint design provides an alternative to conventional steel-timber or timber-adhesive joint solutions. The high level of precision and the ability to articulate every single joint according to its structural and geometric need is achievable through the digital process and the robotic fabrication. (Robeller & Weinand, 2015)

3.2 Reuse of elements

Combinatory algorithms allow to efficiently rearrange elements. If the properties of the elements are sufficiently described the elements could be used in different buildings at suitable positions. As demonstrated with the parametrisation, individual adaption and the joint of gross tree trunks, the potential of this technique to be adapted for the reuse of elements within the timber construction of taller timber buildings appears viable. (Geno et al., 2022). Elements are often designed for a specific use, due to efficiency reasons. Therefore, the reuse of elements could be limited since they may only fit the exact position and situation they are design for. However, with a detailed and exact parametrisation a suitable reuse or a consecutive adaption might be possible.

3.3 Robotic assembly

Robotic assembly of timber elements is not yet implemented into construction practice but it is subject to academic research. Timber members are connected either in a construction site scenario, where the robots operate on site or a prefabrication scenario where the robotic fabrication occurs in an industrial workshop. Industrialised prefabrication is common practice in other industries but still underdeveloped in most parts of the construction industry. However, timber construction is already ahead in terms of prefabrication where construction members are prefabricated with CNC machinery but the actual assembly of elements is mostly manual work. Practical applications of autonomous robotic assemblers for taller timber buildings are obvious and desirable since a higher level of automatization and industrialisation potentially reduces costs and dependencies on weather or other site conditions. Basic research (Leder et al., 2019) demonstrates that the concept of autonomous robots crawling the construction while building it up is viable. Robots, consisting of rotational gripper heads use one side to hold itself and the other to place a new member into the construction.

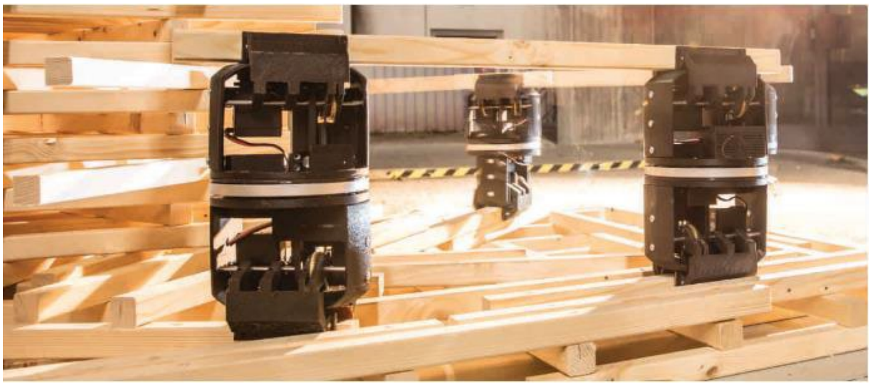

Figure 1: Distributed Robotic Timber Construction (Leder et al., 2019, S. 510), with permission by ICD Uni Stuttgart©.

Apparently, this is early stage research, where the material supply, fixing of elements and the larger distance movement are to yet to be solved. However, it provides a prove of a general viable concept.

Prefabrication of timber constructions as an adaption of already know by conveyor band production in other industries differs by the need of individual elements, since buildings are not produced as a recurring mass product but as individual solutions for specific design problems. While elements within one building recur in small series a highly adaptable and individualised production line is required. Even timber-only joints with rather complex geometry and assembly conditions can be handled with high precision and reliability. (Helmreich et al., 2022).

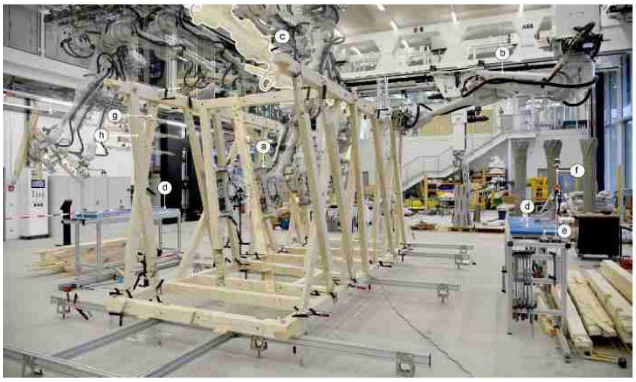

Figure 2: Robotic assembly system (Helmreich et al., 2022), with permission by Gramazio Kohler, ETH Zürich ©.

Robotic handling of the construction and its elements require full digital models since members and their individual positions need to be identified unequivocally. Industrialised and automated production of elements allows for high precision and individualised design of elements which increases robustness, repairability and reusability. Digital models and the corresponding industrial production allow for identical reproduction of elements if needed for repair.

4 Conclusion

Although the timber construction industry appears to be at the fore front of computational design and fabrication methods the construction industry as a large seems to be slow in adopting innovative methods into their processes. While the design often is already accomplished digitally the production is predominantly manually and on site, with low levels of industrialisation compared to other industries like for example the automotive industries. Academic research demonstrates already the general potential of an applied digital process including design, construction, fabrication and erection. The mentioned projects demonstrate that the computational methods and the integrated a digitised design-fabrication process are at the fringes to be adopted into practice.

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Design of taller timber buildings against deformations and vibrations: a state-of-the-art review

Edited by:
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EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Cost Action CA20139

Holistic design of taller timber buildings - HELEN

Working Group (WG) 2

Deformations and Vibrations

State-of-the-art (STAR) report

December, 2022

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Forward

This report is a publication of the European Network **COST Action CA20139** “Holistic design of taller timber buildings – **HELEN**”, established with the aim to “work towards optimized holistic approaches to improve the performance of taller timber buildings and to widen their competitiveness and use across the EU and rest of the world” (https://cahelen.eu/).

The activities conducted in the first year of the Action by the **Working Group (WG) 2** – Deformations and Vibrations - are summarized in this document in the form of a state-of-the-art report (**STAR**) regarding design, analysis and construction methods of taller timber buildings and their components against **deformations** and **vibrations**.

The report is the result of a deep review of scientific literature, international projects, national regulations, design guidelines, as well as case studies.

The information collected in this STAR document represent the starting point of discussion to identify solutions, research targets, methods and resources for the future of taller timber buildings and their design against deformations and vibrations, where a key role is given to experimental methods, performance indicators and research efforts.

Two different sub-groups (SGs) have been defined for WG2 STAR activities, namely **SG1 – Deformations** and **SG2 - Vibrations**. For each SG, different subtopics have been detected among WG2 members, to have extended discussion, and are summarized in present document.

As such, the present report is divided into two major sections and summarizes some major outcomes of STAR. More precisely:

- the first part includes the overview review conducted by SG1 on the “Deformations” issue;
- the review regarding the SG2 “Vibrations” issue is summarized in the second part;
- finally, it is important to note that for both SG1 and SG2 parts of this STAR report, relevant input and discussion on relevant topics and open gaps is provided by active WG2 contributors and affiliated research units

Chiara Bedon (WG2 Leader)

Thomas Reynolds (WG2.SG1 Leader)

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WG2.SG1 – Deformations

Connection types for taller timber buildings

Thomas Reynolds, University of Edinburgh (United Kingdom); **Chiara Bedon**, University of Trieste (Italy); **Angelo Aloisio**, University of L'Aquila (Italy)

1. Introduction

In tall buildings, connection deformation can potentially cause serviceability failures through deflection of the structure (Skidmore Owings & Merrill, 2014; Smith, 2011), and in slender structures could also lead to ultimate limit state failure through second-order P-delta effects (Teweldebrhan & Tesfamariam, 2022). Connection deformation also affects both serviceability and ultimate-limit state behaviour of mechanically-jointed composite beams and slabs, including timber-concrete composites (Yu et al., 2009) and dowel-laminated timber (El-Houjeyri et al. 2019). The stiffness of connections is also a key parameter in modelling for vibration and acoustic serviceability (Edskär & Lidelöw, 2019; Tulebekova et al., 2022), to ensure, for example, occupant comfort or usability of sensitive instruments. Seismic design also requires modelling of connection stiffness and ductility. An overview of most recent studies and issues is summarized in the following paragraphs.

Figure 1: Connections for the Mjøstårnet building, with large groups of steel dowels passing through multiple slotted-in steel plates. Reproduced from (Abrahamsen, 2018).

2. Connection types

2.1. Dowel-type connections

Dowel-type connections include nails, screws, bolts and dowels, and are the most common way to create connections between timber elements on a construction site. Many different types of connections rely on dowel action, where a (usually steel) connector acts across a shear plane to hold two parts together. Examples include slotted-in steel plates with bolts or dowels passing through the timber and the plate (Abrahamsen, 2018: Dorn et al., 2013; Reynolds et al. 2022), timber-to-timber connections where the connector passes through over- lapping timber elements and steel hold-downs or angle-brackets which are secured to the timber with nails or screws (Ringhofer et al. 2018). Dowel-type connectors are also used to connect pieces of solid wood to create larger building elements, such as in nail-laminated (Hasan et al., 2019) or dowel-laminated timber [8, 49]. Their force-displacement response of dowel-type connections is highly nonlinear, because of gap opening and construction tolerances (Reynolds et al., 2022), nonlinear, irreversible material behaviour, even at low loads (Bader et al., 2016; Dorn et al., 2013).

2.2. Connections resistant to withdrawal

Nails, screws and bolts can also be used in connections which apply force along their axis. In this mode of loading they transfer load into the timber by resisting withdrawal. Part of the behaviour of hold-downs or angle brackets relies on this mode of loading. Long screws used for reinforcement, particularly against perpendicular-to-grain splitting, are loaded in axially, relying on withdrawal resistance (Dietsch & Brandner, 2015; Jockwer et al., 2016; Trautz & Koj, 2009). Screws are generally stiffer when loaded axially than they are in shear (also known as dowel action).

2.3 Connections in timber-concrete composites for flexure

Timber-concrete composites require a shear connection between the concrete and timber to ensure composite action. Connection stiffness is crucial here, and thus while connectors such as nails and screws have been used, they are commonly inclined to take advantage of their increased stiffness in withdrawal (Yeoh et al., 2011). Various numerical investigations are available in literature for the accurate mechanical characterization, especially concerning the testing setup issues (Bedon & Fragiacomo, 2019; Bedon et al., 2021) The steel connectors can also be removed by casting the concrete into grooves to provide interlock between the layers, or by using an adhesive connection between layers (Frohnmüller et al., 2021), which can achieve an almost fully composite section. Combinations of screws and adhesive have also been used to increase the ductility after initial failure of the adhesive (Braun, 2020).

2.4 Acoustic barriers

Acoustics is often an important design driver for lightweight construction systems such as timber (Olsson & Bolmsvik, 2008). Transmission between a “source room” and a “receiving room” can be airborne or structure borne. Acoustic separation is often achieved using a connecting layer much softer than the timber of structural elements above and below the insert. To prevent acoustic bridges via connections, soundproofed steel angle brackets have recently been developed, in which the rigid parts are elastically separated from one another using interlayers. Elastomers are frequently used at junctions so as to reduce low frequency noise. Common types include closed cellular polyurethane and mixed cellular polyurethane. The influence of flexible sound insulation layers on the deformation of timber systems has been studied (Azinović et al., 2021; Kržan & Azinović, 2021), showing a small influence on strength, but a large influence on deformation, and suggesting methods to mitigate this effect (De Santis & Fragiacomo, 2021).

2.5 Adhesive connections

Adhesive connections are vital for creation of laminated timber elements, but are also used in structural joints between elements (Angelidi & Thomas Keller, 2018; Angelidi et al., 2018; Vallée et al., 2017). Adhesive connections are generally considered to be rigid for practical engineering design purposes, but flexible adhesive joints have been proposed for structural joints in seismic regions (Azinović et al., 2021; Śliwa-Wieczorek et al., 2020a; 2020b; 2021), and to increase the capacity of laminated timber (Szeptyński, 2020). Flexible connections between elements in bending affect the level of composite action which can be achieved, and a variety of methods are used in research to assess the bending strength and stiffness of the resulting system, including experimental, analytical (e.g. the gamma method) and numerical (finite element analysis), see (Jelušič & Kravanja, 2018). Experimental and CZM-based numerical analyses accounting for moisture and adhesive types are reported in (Barbalić et al., 2021; Bedon et al., 2022).

Design methods and experimental approaches for connections in taller timber buildings

Thomas Reynolds, University of Edinburgh (United Kingdom); **Chiara Bedon**, University of Trieste (Italy); **Angelo Aloisio**, University of L'Aquila (Italy)

1. Design methods and limits

EN 1995-1-1 (Eurocode 5) uses empirical equations to assign an elastic stiffness to joints (referred to as the "slip modulus" K_{ser}). The derivation of these equations is described by Ehlbeck & Larsen (1993). Through the equations, a stiffness is assigned per shear plane per connector, based only on dowel diameter and density, and then multiplied by the number of shear planes and the number of connectors. Modifications are then applied for service class and duration of loading.

1.1. Theoretical descriptions and modelling

The force-deformation behaviour of connections is non-linear in various ways, as described in (Dorn et al., 2013) and shown in Fig. 1. Behaviour under initial loading follows a different path to unloading and reloading, which means that the deformation is dependent on loading history as well as the applied load at a particular time.

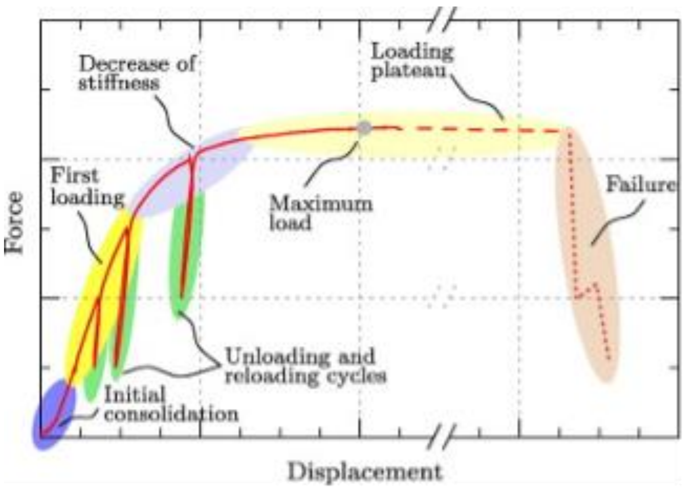

Figure 1: Generalised force-displacement response of a dowel-type connection with a slotted-in steel plate. Reproduced from (Dorn et al., 2013) with permission from Elsevier®, license agreement 5420820441315, November 2022.

Experiments on dowel-type connections (Sandhaas et al., 2017) show that dowel stiffness is not generally well predicted by the EN 1995-1-1 equation for K_{ser}, especially when the connection contains multiple dowels or dowels of unusual dimensions. In multi-storey timber buildings, other effects on deformation may assume in- creasing importance due to the scale of the structure. In timber both creep and moisture-induced strains are significant and their effect has been measured in a multi-storey timber building (Yu et al., 2009). It should be noted that the building considered in that study was designed to mitigate the creep and moisture-induced strains by avoiding loading timber perpendicular to grain in floors, thus the effect might be expected to be larger in buildings with platform construction. In platform-frame cross-laminated timber buildings, the friction between the panels creates relatively rigid connections in the serviceability limit state, and the dynamic stiffness has been shown to be well predicted based on panel deformation (Reynolds et al., 2015).

1.2. Diaphragm behaviour of floors

Whenever timber is used in the floors of multi-storey buildings, its capacity to act as a diaphragm, transferring load to the lateral load resisting system is important (D'Arenzo et al., 2019; Moroder et al., 2015; Moroder, 2016; Moroder et al., 2016). Since timber floor plates, even in CLT, are rarely made from one continuous element, deformation in connections is a key driver of the overall diaphragm action in the floor (D'Arenzo et al., 2019). Timber diaphragms tend to be more flexible than their concrete counterparts, with increasing floor spans further reducing stiffness.

2. Experimental methods

The EN 1995-1-1 (Eurocode 5) cites the experimental method in EN 26891 for experimental determination of the stiffness of joints. These standards describe the stiffness of joints as the "slip modulus", and it is assigned an elastic stiffness based on the secant stiffness of the joint under first loading between 10% and 40% of its estimated failure load.

2.1. Group effects in multi-dowel connections

The strength of a dowel-type connection does not increase linearly with the number of connectors. This has been well studied (e.g. (Blaß, 1990; Hossain et al., 2019; Nozynski, 1980)), however the same appears to be true of the stiffness of connections, and tests have been carried out with varying numbers of fasteners to quantify this effect (Jockwer & Jorissen, 2018a; Reynolds et al., 2022).

2.2. Long-term performance

Wood exhibits time-dependent deformation (de Borst et al., 2013; Holzer et al., 1989; Ozyhar et al., 2013; Ranta-Maunus, 1990). Given the interaction between timber and connector in a connection, that time-dependent deformation is also exhibited by connections (Reynolds et al., 2013).

2.3. Composite action in beams with connection deformation

The use of ductile adhesives may allow designing ductile joints, which can compensate for the material ductility that timber lacks. The effect of the different adhesives on the joint capacity and ductility has been studied and quantified. Strain field measurements using the Digital Image Correlation (DIC) technique and a quadratic strain interaction criterion provided a better understanding of the mechanical behaviour of the two different joint types (Angelidi & Keller, 2018; Angelidi et al., 2018).

2.4. Monitoring structural integrity

Monitoring the condition of timber structures naturally requires assessing the condition of connections, and stiffness and deformation behaviour is a good candidate for non-destructive assessment of connections (Serdjuks et al., 2022).

Beam-on-foundation (BoF) modelling for stiffness prediction of laterally loaded dowel-type connections in taller timber buildings

Michael Schweigler, Linnaeus University (Sweden); **Romain Lemaître**, Fire Testing Centre, CERIB (France) ; **Thomas K. Bader**, Linnaeus University (Sweden)

1. Introduction and background

In taller timber buildings, serviceability limit state verifications, like the deformation verification are the predominant design cases. However, corresponding design concepts in the current design codes, like e.g. in Eurocode 5 (EN1995-1-1), are based on simplified empirical equations, developed for deformation insensitive timber structures, and thus, are not suitable for a reliable design of taller timber buildings. Due to the large number of connections, substantially contributing to the global structural stiffness of taller timber buildings, a suitable and reliable prediction of the connection stiffness is essential. The design model for the prediction of the stiffness of connections needs to include effects of multiple shear planes, a large number of fasteners in a row, as well as the effect of fabrication tolerances. Validation of the beam-on-foundation (BoF) approach (see e.g. Hirai, 1983; Bader et al., 2016), a computationally efficient numerical model for the behaviour of laterally loaded connections, has shown that the method is perfectly suited to study these large number of influence factors on the connection stiffness, without the need for cumbersome and expensive experimental testing programs. In this contribution, we like to present this engineering modelling approach based on the finite-element method, and its application to predict the stiffness of laterally loaded dowel-type fasteners in multiple-fastener connections. For this purpose, the BoF-model for the prediction of the non-linear load-displacement behaviour of the single fastener is combined with 2D plate elements, which allow to consider the wood member elasticity or steel plate elasticity in between the fasteners. This allows for example for evaluation of group effects on the joint stiffness, serving as basis for proposal of engineering design rules.

2. Beam-on-foundation model (BoF)

BoF-models are used for the prediction of properties of mechanical connections since the early thirties of the last century (Hager, 1930; Kuenzi, 1955; Norèn, 1968; Wilkinson, 1971; Hirai, 1983). However, these approaches have remained unused in practical design due to their complex implementation and their high running time, at the time of their invention, while today computational resources allow for fast and efficient numerical methods-based design. Models of different complexity were used from simplified (i) rigid-ideal plastic models, which allow only for strength prediction (cf. Johansen (1949)); to (ii) bi-linear elastic approaches, being able to predict stiffness and strength (Sawata & Yasumura, 2003; Cachim & Franssen, 2009), and (iii) nonlinear elastic models, which are optimized for numerical simulations (e.g. Lemaître et al., 2018). BOF-models might be even used for earthquake design by application of plastic, or even hysteresis models (Izzi et al., 2018; Girhammar et al., 2017). In recent years, the validity of the BoF approach for efficient prediction of the connection stiffness and even capacity was proven by several contributions, like (Bader et al., 2016; Schweigler et al., 2016; Lemaître et al., 2018a ; 2018b ; 2019 ; 2020 ; De Santis et al., 2021; Schweigler et al., 2021).

3. Embedment stiffness definition and prediction

To support the design with reliable input data related to the load-deformation behaviour of steel dowels embedded in wood or wood-based products, Schweigler et al. (2019) provided a large database of embedment parameters for different wood species and wood products. For a common basis, a procedure to measure and define embedment stiffness and strength parameters was proposed, and subsequently applied for compilation of an embedment database. It was even aimed to provide correlation equations of embedment parameters with characteristic wood properties, like e.g. the elastic embedment stiffness, $k_{f,el}$, with the wood density, ρ. The analysis of this database showed no distinct correlation between the dowel diameter and the elastic embedment stiffness. However, in previous scientific works, other type of prediction equations to predict embedment stiffness were proposed with other parameters such as the wood elasticity modulus, E_0, and the dowel diameter, d (see Table 1).

Table 1 – Design equations for embedment stiffness (in N/mm²/mm).

	Harada (1951)	Wilkinson (1971)	Nakatani and Sawada (1980)	Hirai and Sawada (1982)	Bléron (2000)	Schweigler et al. (2019)
$k_{f,el}^{first\ loading}$	$\frac{E_0}{140}$	–	$\frac{E_0}{17.8 \cdot d + 16.1}$	$\frac{E_0}{10.9 \cdot d + 31.6}$	$\frac{k_{f,el}^{reloading}}{A^*}$	$0.1374 \cdot \rho - 12.29$
$k_{f,el}^{reloading}$	–	$0.87 \cdot \rho$	$\frac{E_0}{5.67 \cdot d + 11.4}$	Unknown	$\frac{1.9 \cdot \rho_k}{d^{0.98} - \frac{1.9 \cdot \rho_k}{245}}$	–
ρ (kg/m³)	Unknown	$\{380 - 710\}$	$\{420 - 770\}$	440 (CoV 4.8 %)	$\{375 - 412\}$	$\{380 - 850\}$
d (mm)	$\{5 - 23\}$	$\{2 - 6\}$	$\{2 - 10\}$	$\{8; 10; 12\}$	$\begin{Bmatrix} 12; 14; 16; \\ 18; 20 \end{Bmatrix}$	$\{12; 16; 20; 24\}$
Nb. of tests	Unknown	≈ 15	≈ 40	≈ 50	100	1565
Testing Method	Unknown	Joint and compression	Half-hole	Joint	Full-hole	Full-hole

$A^* = 30.502 - 5.0545 \cdot d + 0.2866 \cdot d^2 - 0.0052 \cdot d^3$

4. Connection stiffness prediction

Mathematical functions, like e.g. the approach from Foschi (1974), allow to define load-displacement curves based on the embedment parameters from the embedment database, which then serve as input to the BOF-model for prediction of the connection stiffness and capacity. A summary of such methods is given in Schweigler et al. (2018). A review of prediction equations for connection stiffness can be found in Loferski (1980) and Jockwer & Jorissen (2018b). In Table 2, the main results are summarized.

Table 2 – Design equations for timber-to-timber connection stiffness (one fastener and one shear plane in N/mm).

Equation	Reference	Method	Fastener type
$0.043 \cdot \rho_m^{1.5} d$	EN 1995-1-1	Test	Bolts, dowels, screws, pre-drilled nails
$3.000 \cdot \rho_k^{0.5} d^{1.70}$	SIA 265	Unknown	Bolts, dowels, screws, pre-drilled nails
$1/(2(L_1 + L_2) - (J_1 - J_2)^2/(K_1 + K_2))^*$	Kuenzi (1955)	Theory	All types
$3.562 \cdot k_{f,el}^{0.75} d^{1.75}$	Wilkinson (1971)	Test + theory	All types
$3.562 \cdot k_{f,el}^{0.75} d^{1.75} \cdot \tanh(\mu \cdot t_1)^{**}$	Sawada (1976)	Test + theory	All types
$29.0 \cdot d^{2.24}$	Jockwer & Jorissen (2018)	Test	Bolts, dowels

* with L_1, L_2, J_1, J_2, K_1, and K_2 defined from hyperbolic functions, see (Kuenzi, 1955)

** with $\mu = \sqrt[4]{k_{f,el} \cdot d/(4E_sI_s)}$ and t_1 the thickness of outer timber members

Most prediction equations are limited to single-dowel connections. Nevertheless, some effort was done to predict design equations for the stiffness of a group of fasteners in timber-to-timber connections by applying nonlinear regression analysis based on numerical simulations (Lemaître et al., 2019), and based on experimental results (Jockwer & Jorissen, 2018). Modeling strategies for groups of fasteners are summarized in Bader et al. (2017). The BoF-model has proven to be more suitable than utilizing experimental results since more parameters can be integrated, such as the drilling tolerance, thickness of connection members, multi-materials, number of fasteners in a row, number of rows of fasteners, or multiple shear planes connections. Another application of the BoF-model could be the stiffness prediction for ultimate limit state design, since the BoF-model is able to predict the nonlinear load-slip curve of a laterally loaded connection. Today, this value is given as a rough estimate by 2/3 of the connection stiffness in the serviceability limit state (EN1995-1-1).

Impact of the non-linear load-deformation behaviour of joints on the performance of timber structures

Dorotea Caprio, Chalmers University of Technology (Sweden); **Robert Jockwer**, Chalmers University of Technology (Sweden)

1. Background

The design of joint is critical for the design of timber structures. In fact, the load-carrying capacity and the mechanisms of collapse of structures strongly depend on the structural configuration and the load-deformation behaviour of joints. The precise understanding and exact characterization of the mechanical behaviour of joints is therefore of great importance in order to be able to build high performance timber structures. Currently, in design standard EN 1995-1-1 (Eurocode 5), rigid-ideally plastic limit design approach for the calculation of connection strength and empirical formula of elastic stiffness that depends on few parameters of influence are used (EN 26891). Moreover, uncertainties related to stiffness and ductility are not considered. In research, large numbers of experiments on the connections have been performed by researchers, in the attempt to determine the capacity of connections and impact of the various geometrical and material parameters. However, many questions remain open, in particular about the stiffness and ductility of connection, since studies often focus on the load-carrying capacity. Stiffness and ductility are fundamental characteristic to be defined, since affect the distribution of forces in the elastic phase and failure mode of structure.

2. Impact of connection non-linearity on reliability

A parametric and sensitivity study on a simple statically indeterminate structure has been performed in (Caprio et al., 2022). The mechanical behaviour of joints has been simplified as elastic-perfectly plastic behaviour. The uncertainties related to bending capacity, stiffness and ductility of joints have been considered. Based on this study, the conclusions are the following:

- Stiffness and ductility have a strong impact on reliability against collapse of the structure
- The simple deterministic considerations on stiffness and ductility might not always be adequate for the evaluation of the reliability of the entire structural system
- For complex or statically indeterminate timber structures, the classical element-by-element verification might not be appropriate and reliability-based analysis should be preferred.

Therefore, the realistic description of mechanical behaviour of joints and the understanding of related uncertainties cannot be ignored.

3. Characterisation of connection non-linearity

The nonlinear load-deformation behaviour of the connection is a consequence of the nonlinear single fastener slip behaviour (Schweigler et al., 2018). Analytical parametric equations can be used to represents the nonlinearities.

Analytical equations for the description of slip behaviour of joints have been proposed by previous researchers. The equations are based on exponential, power functions, a combination of the two or polynomials. Detailed summary of different models for the analytical description of the load-deformation behaviour of joints is given in (Schweigler et al., 2018) and (Flatscher, 2017). The joint load does not only depend on slip, but also on other parameters, such as fasteners-to-grain angle, dowel diameter, wood species, density etc. For example, the behaviour of single self-tapping screw is a lot sensitive to screw to grain angle, as illustrated in Fig. 1.

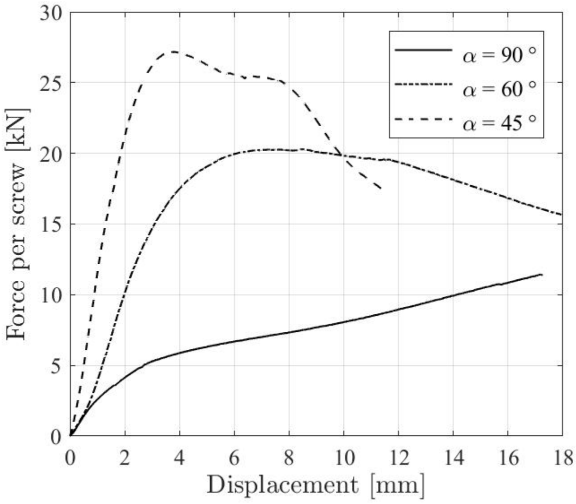

Figure 1: Examples of the different load-deformation behaviour of screw connections with different angles α between screw axis and load application described in (Jockwer et al., 2014).

Following the same multi-step approach illustrated in (Schweigler et al., 2018), first analytical equations (polynomials or exponential or other) are fitted to experimental determined slip curve for different value of the selected parameter of influence (for example screw to grain angle), then in a second step regression analysis is applied to each coefficient of the analytical equation to connect it to the parameter of influence. These two regression steps can be combined in a third step. This step can be repeated for other parameters (Schweigler et al., 2018). The starting point is data-set of experiments on timber joints that can be used for this multi-step approach.

4. Conclusions and ongoing work

The main conclusions are:

- Realistic representation of nonlinear behaviour of joints and related uncertainties are important for the analysis of reliability of structures
- Realistic representation of joints and related uncertainties might serve as input for numerical models that uses spring elements to model the behaviour of joints.

Currently, a review about the most important mechanical, geometrical and load related parameters that affect the behaviour of dowel-type joints, joints with glued-in rods and joints with self-tapping screw is being carried out. The ability of different analytical models to approximate the non-linear slip behaviour of common timber joints is being discussed. Coefficients of analytical model can be determined using non-linear least square regression or they can be determined manually from the experimental curve. The two approaches will be compared. In the next step experimental data will be used to link the selected mathematical model to the most influential parameters (density, fastener to load angle, diameter etc).

Stiffness of dowel-type connections

Robbe Celis, WOOD.BE (Belgium)

1. Stiffness of connections in context of Eurocode 5

In Eurocode 5 stiffness of timber dowel-type connections is defined via a slip modulus (N/mm) for a single dowel and per shear plane. The stiffness of a connection is thereby found by multiplying by the number of fasteners, and the number of shear planes. This leads to a single, linear value for the connection stiffness. Two factors are taken into account by the formulas set forth in EN 1995-1-1 (Eurocode 5): dowel diameter and mean density of timber. Depending on the type of fastener, the diameter and density are raised to a certain power. For predrilled bolts, nails, screws:

$$K_{ser} = {\rho_m}^{1,5} \frac{d}{23} \tag{1}$$

The connection stiffness is an important value in timber engineering. As the translational and rotational stiffness of the connection is determined by the stiffness of the single dowel, the force distribution in a construction can be heavily influenced by the single dowel stiffness. In shear walls, the interaction between panel and timber, has an important influence on the load/deformation behaviour of the wall. When designing higher timber buildings, the influence of connection stiffness plays an important part in the behaviour of the whole structure. When designing for robustness, ductility of connections is a very important design parameter.

2. Problem with the current description of connection stiffness

It is clear that the dowel-type connection deformation behaviour is not linear. K_{ser}, and K_u, do not allow for any design taking into account the real non-linear behaviour of connections. A first issue therefore is the implication that designing for robustness through ductility is hindered by the limitations of the current slip modulus. Secondly, the load distribution between fasteners within a connection, specifically in the case where rotational and translational forces are combined, is heavily influenced by the non-linear behaviour of the single dowel. It is furthermore not possible to take realistically into account the influence of connection stiffness on the force distribution within a structure. Lastly, the current formulas do not allow for evaluation of modern building techniques using interlayers (e.g., acoustic separating layers).

3. Current state of the art

The field of connection stiffness is still a developing one. For optimal use in construction design, not only more information on the non-linear behaviour is needed. As the influence of connection stiffness can be both positive and negative, it is appropriate to possess information on both upper and lower limits for the stiffness, in addition to mean values.

3.1. Parameters

Different parameters can be identified to play a role:

- As already defined in Eurocode 5:
    - Dowel diameter
    - Timber density
- Other parameters not taken into account:
    - Thickness of timber members (linked to failure mode)
    - Direction of loading versus the grain of the timber
    - Axial effects: rope effect
    - Steel quality
    - …

3.2. Measurement examples

Following examples are a result of the research project WOODLINK: on stiffness of connections, executed by WOOD.BE, and supported by the Belgian government. These results are not yet published. The first graph is an illustration of the real load-deformation behaviour of a single nail connection between two LVL blocks. It is clear that K_{ser} as defined by Eurocode 5 does not describe this behaviour adequately.

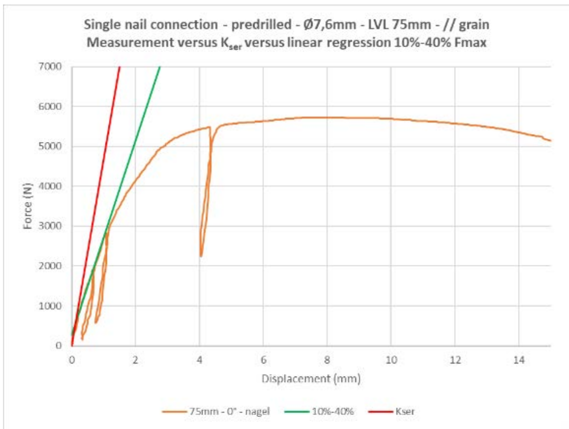

Figure 1. Test result single nail loaded in shear.

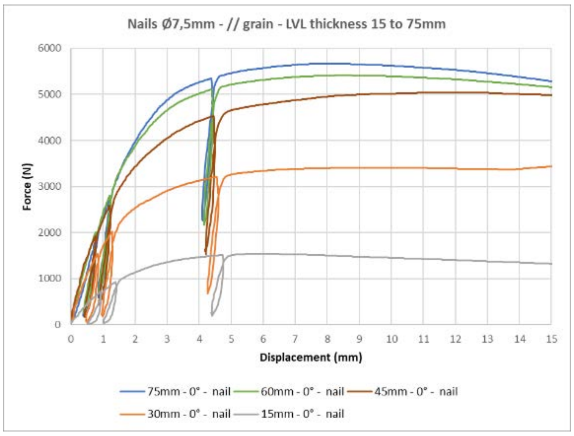

Figure 2. Timber thickness versus load-deformation behaviour.

The next graph illustrates the influence of the thickness of the timber members. The LVL members were varied between 15 and 75mm, in steps of 15mm. As the failure mode passes from timber failure (mode c) to dowel failure (mode f), a limit is reached in terms of strength, as well as stiffness. The final picture gives an overview of the test results versus K_{ser} as defined by. The shown values for the stiffness are defined as a linear regression of the load-deformation curve, between 10% and 40% of the maximum force up to 15mm displacement.

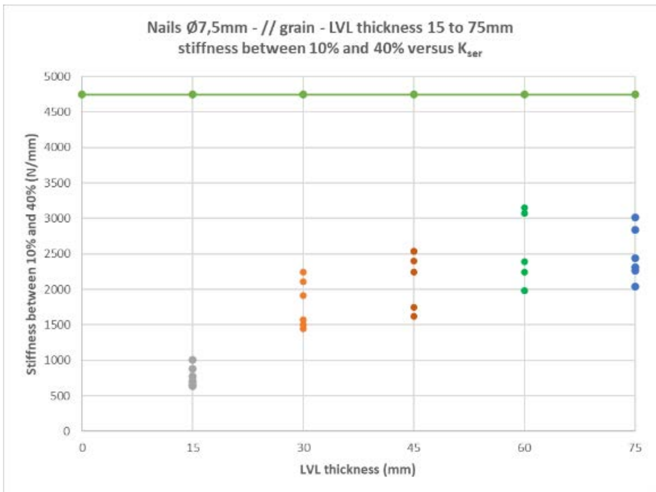

Figure 3. Measured stiffness versus K_{ser} for varying timber thickness.

3.3. Models

A promising model that can be used to evaluate the stiffness of dowel-type connections is the so-called beam-on-foundation model. In this approach, the single dowel is modelled as a discrete number of elements, by use of finite element modelling. The reaction of the wood is modelled by use of non-linear springs, which can be obtained by way of embedment testing following EN 383. The discrete elements of the dowel are connected by means of rotational springs who simulate the plastic hinges in the dowel. In this simple model, no axial effects are taken into account, but test do show axial effects may be considerate, especially in the plastic domain. This type of model allows for more complicated connection layouts, and for example the integration of interlayers.

4. Conclusions

The influence of connection stiffness on structural design can be of great importance. Today a conservative approach towards this influence is necessary. Refinement of the current stiffness models could be a means to a more robust and effective design.

Effect of soundproofing interlayers on the strength and stiffness of CLT wall buildings

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1. Introduction

Acoustics is often one of the main problems for timber buildings. Typical irritating sounds are people talking, television and footsteps. Transmission between two rooms can be airborne or structure borne. Sound can reach the "room of the listener" through various transmission paths: the separating wall itself could radiates sound energy directly into the room of the listener, the separating wall could transmit vibration to the adjacent walls, which radiate energy into the listener room, the side walls of the "source room" could transmit vibrations to the separating wall or to side walls of the listener room (Hagberg & Ingemanssin, 2009; Rothoblaas - Flanksound project; ISO 12354-1). All sounds that propagate through propagation paths other than direct transmission through the separating wall or floor are called flanking sounds. It is essential to solve the problems of flanking transmission in order to deal with the sound insulation. Flanking sound can be reduced limiting the vibrations transmitted to the contiguous walls and floors in the source room, reducing the radiation of sound from the walls and floors of the receiving room and reducing the vibrations transmission from the elements of the source room to the elements of the receiving room. The latter strategy requires a complete separation of the structural and non-structural part of the adjoining apartments from each other.

2. Separation with soft layers

Separation is often achieved using layer significantly softer than the timber of structural elements above and below the insert. In the vertical direction, the separation is achieved using an elastic layer between overlapping walls and between floors and walls (Ljunggren & Ågren, 2013; Karacabeyli & Lum, 2014). However, the layer is subjected to the static load of the section of the building above the layer. This means that stiff layers must be used in the lower part of high buildings, increasing coupling and thus degrading the sound insulation. Acoustic bridges via connections can be prevented by soundproofed steel angle brackets.

In the soundproofed connections the rigid parts are elastically separated from one another using interlayers (Fig. 1). Elastomers are frequently used at junctions so as to reduce low frequency sounds. Common types include closed cellular polyurethane ("CCP") and mixed cellular polyurethane ("MCP"). Since the choice of the most adequate properties for the material is essential, elastomers should be characterized defining Young's and shear moduli for varying load-frequencies. Admissible vertical loads that guarantee the maintenance of the insulating properties and admissible shear strain must also be defined (Negreira et al., 2014; Reichelt et al., 2016). The coefficient of elastomers on timber can be estimated as $\mu \geq 0.5$ and therefore it is useful to take the load transmission capability of the elastic layers into account and design. Although separation is an efficacious solution of the sound insulation problem, it is often not the most straightforward since there might be a conflict against the building's overall deformability and stability requirements. Therefore, elastic connection must be carefully designed in order to allow the structure to appropriately manage the horizontal wind and seismic loads.

3. Mechanical behaviour of soundproofed connections

The influence of flexible sound insulation layers on the seismic performance of cross laminated timber walls has been studied in (Azinović et al., 2021). According to the authors the bedding insulation layer under the wall led to only minor changes in the load-bearing capacity of the walls under lower vertical loads but the stiffness of the wall decreased to less than 40% that of the uninsulated wall, due to additional lateral deformations enabled by the insulation. Experiments confirmed that a higher vertical load substantially increases the load bearing capacity, as well as the stiffness of the shear wall, due to the associated increase in friction.

Figure 1: Soundproofed steel-to-timber connection.

The cyclic response of insulated steel angle brackets with inclined and perpendicular screws used for cross-laminated timber connections has been assessed in (Kržan & Azinović, 2021). The monotonic and cyclic tests on the CLT wall-to-floor connections highlighted that insulation under the angle bracket has a marginal influence on the load-bearing capacity; however, it significantly influences the stiffness characteristics resulting in a 22% and 45% reduction of the effective stiffness in pure shear and tensile loading respectively. The relative energy dissipation and equivalent viscous damping coefficient were lower for the insulated specimens than for the uninsulated specimens, but the difference decreases with increasing displacements and repeated cycles. Friction energy dissipation was found.

Recently, De Santis & Fragiacomo (2021) proposed an analytical model for the stiffness prediction of screw connection with deformable interlayers. The authors found that for connections with screws inclined with respect to the sliding plane, the slip modulus decreases much slower than for connections with perpendicular screws as the thickness of the intermediate layer increases.

Moment resisting timber frames using connections based on threaded rods

Osama Abdelfattah Hegeir, NTNU, (Norway); **Haris Stamatopoulos**, NTNU (Norway)

1. Introduction

Timber buildings are prone to wind-induced vibrations due to their light weight and moderate stiffness. Excessive wind-induced accelerations can cause discomfort to the building's occupants, and lateral displacements can damage or affect the functionality of the building. Therefore, in multi-storey timber buildings, wind-induced accelerations and displacements are typically among the main design criteria. There are several structural systems that can be used as lateral load resisting systems, such as CLT shear walls, diagonals, and moment resisting frames (MRFs). MRFs are advantageous considering the architectural flexibility since they impose fewer architectural restrictions and provide more open space.

2. Moment Resisting Timber Frames (MRTFs)

A MRTF structural system was proposed at NTNU (Vilguts et al., 2021), see Fig. 1 (a). The system consists of continuous glulam columns connected to glulam beams using semi-rigid moment connections with rotational stiffness K_{θ}. A Parametric study using 2D plane frame model (Fig. 1 (b)) (Vilguts et al., 2021) has shown these MRTFs can be used up to 8-10 storeys considering lateral displacements and wind-induced accelerations (serviceability requirements). In the study (Vilguts et al., 2021), the spacing between adjacent frames was limited to 2.40 m. A minimum of 10000-12500 kNm/rad beam-column connection stiffness was proved necessary to meet the serviceability requirements (Vilguts et al., 2021). An example of the serviceability performance of such MRTFs by use of a linear-elastic model is shown in Fig. 2. The calculation of wind-induced accelerations was based on modal analysis of the frame and the approach described in EN1991-1-4 (Eurocode 1). Fig. 2 shows that a significant improvement can be achieved with respect to both accelerations and lateral displacements when semi-rigid beam-to-column connections are used. Therefore, the investment in such connections is of great importance.

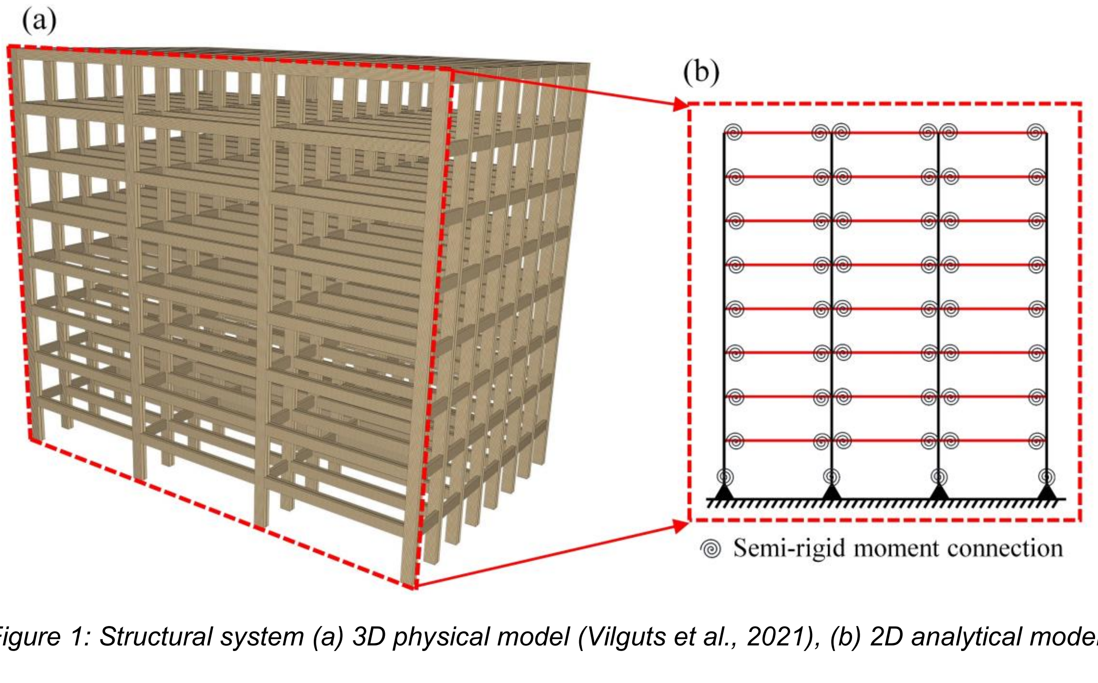

Figure 1: Structural system (a) 3D physical model (Vilguts et al., 2021), (b) 2D analytical model.

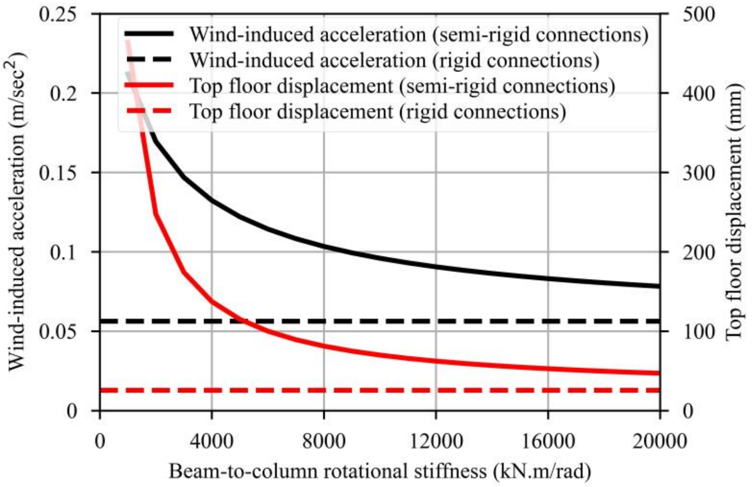

Figure 2: An example of improved performance of a 3-bays 10-storeys MRTF (wind velocity = 26 m/sec-linear elastic analysis).

In addition to the improved lateral performance of the structure, vertical deflections and vibration performance of floors are improved if semi-rigid moment connections are used. A parametric study using a simple beam model (Malo & Stamatopoulos, 2016) has shown that the use of semi-rigid connections can significantly improve the human-induced vibration performance relative to pinned connections, allowing for longer spans. In the study (Malo & Stamatopoulos, 2016), Hu and Chui vibration criterion (Hu & Chui, 2004) was used as an indicator to evaluate the performance of the beam. Fig. 3 shows the relative performance of the human-induced vibration of a simple beam. The relative performance is the ratio between the performance of a beam with semi-rigid connections to the performance of the same beam with pinned connections (minimum value is unity). A possible range of K (normalized connection stiffness: $K_\Theta l/EI$ where K_Θ is the rotational stiffness of the beam) assuming a reasonable connection stiffness for timber beams is 0-5, confer Fig. 3 (a).

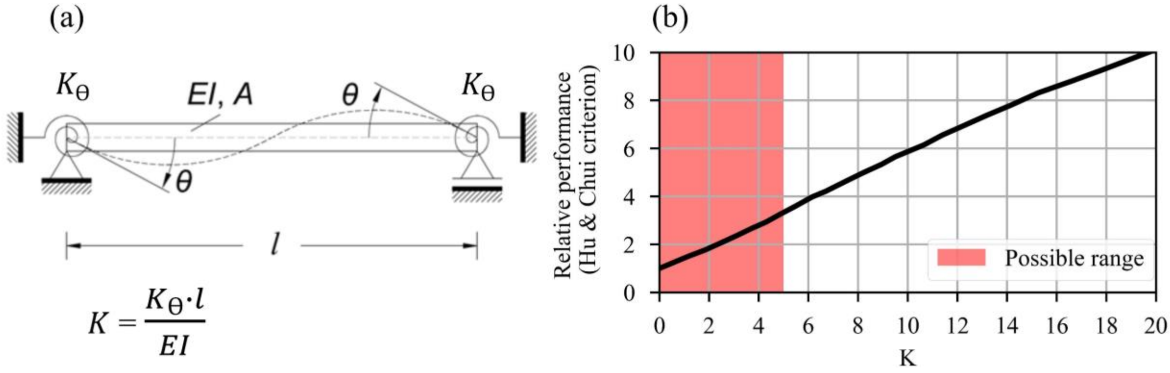

Figure 3: (a) Analytical model of beam and (b) vibration relative performance (Malo & Stamatopoulos, 2016).

3. Semi-rigid moment connection using threaded rods-experimental work

Achieving moment connections with good stiffness is challenging in timber structures. Threaded rods have shown good strength and stiffness properties when loaded axially, see e.g.(Stamatopoulos & Malo, 2020) for a summary. Several variations of moment connections based on threaded rods have been investigated experimentally, e.g. (Malo & Stamatopoulos, 2016; Vilguts et al., 2022; Vilguts et al., 2021). These connections have shown satisfactory stiffness; however, research is still ongoing to achieve further improved properties with respect to stiffness, capacity, ease of assembly etc. Fig. 4 shows some examples of moment connections based on threaded rods developed and tested at NTNU.

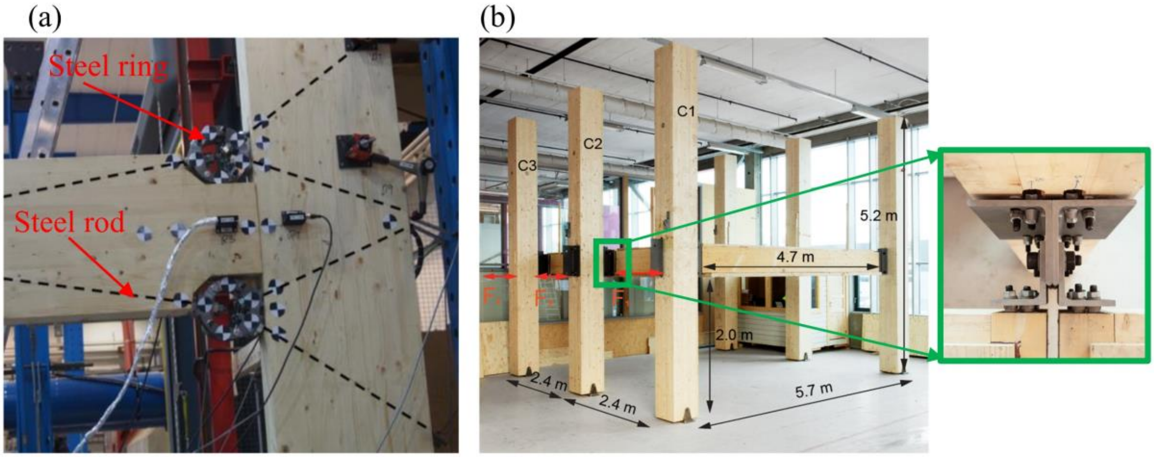

Figure 4: Examples of Moment connections (a) full scale connection (Stamatopoulos et al., 2022) , (b) full scale mock-up (Vilguts et al., 2022).

4. Semi-rigid moment connection using threaded rods-analytical work

Additional to the performed experimental work, structural simulation using finite element method (FEM) was also used to investigate the behaviour of moment resisting connections based on threaded rods (Vilguts, 2021), see e.g. Fig. 5. Analytical models have also been developed and verified using experimental work (Stamatopoulos et al., 2022).

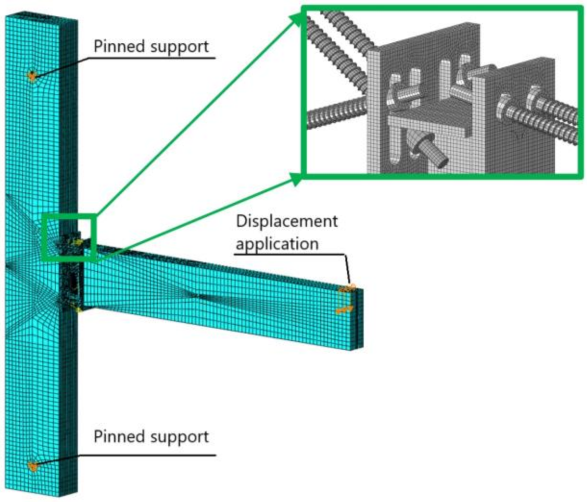

Figure 5: Examples of FEM simulation of moment connections (Vilguts, 2021).

5. Conclusions and future work

This contribution provides a brief summary of an ongoing research at NTNU on MRTFs, and semi-rigid moment connections based on threaded rods. MRTFs have shown applicability to build up to 8-10 storeys with out-of-plane spacing between adjacent frames of 2.40 m considering serviceability requirements. Further research is needed to extend the applicability of such system to taller buildings and larger out-of-plane spacing. The capacity and ductility of connections are of great importance and should also be investigated to pave the way for using such connections in practice.

Experimental Investigation of CLT Connection Deformation

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1. Introduction

Cross laminated timber (CLT) is an innovative engineered wood product, especially as a shear wall in order to meet the rigidity and strength requirements in multi-storey timber buildings. Many experimental studies have been devoted to comprehending and developing the seismic performance concerning the connections of CLT panels under seismic loads so far. CLT panels have major rigidity regarding the linked connections and in experimental tests is commonly observed an elastic behaviour in the panels and an inelastic behaviour in the connections (Popovski et al., 2014; Sullivan et al., 2018). CLT panels are linked with metal connectors (angle bracket, hold-down, metal plate, etc.) via nail, screw, dowel, etc. fasteners that coated different chemicals to resist corrosion in damp conditions. Metal connections are related to the withdrawal strength of fastener, or holding capacity, as well as shear strength. To focus the withdrawal resistance of a single fastener instead of a group under interaction will be an economical and realistic method to predict the pullout performance per fastener as well as to prevent failure modes. Therefore, the withdrawal resistance of a single fastener from a CLT specimen, which has not been adequately investigated so far, is systematically addressed by shank threated nails and wood screw in (Ceylan & Girgin, 2020) study. As a result of the evaluation obtained from the withdrawal resistance tests, the highest withdrawal strengths were attained in domestic phosphate-coated annular ring nails, and these nails were used in CLT wall-to-floor connections tests in the next. The detailed results of experimental studies are also included in the PhD thesis (Ceylan, 2021).

2. Withdrawal resistance of resin and phosphate coated annular ring nails in CLT specimens

The galvanized fasteners (ring nail, helical nail, screw, etc.) are common in timber engineering that connected the angle brackets, hold-downs, plates, etc. Although chemical coating (esp. galvanized) is generally used for treatment, no article has been found for resin or phosphate coated annular nails, except for Ceylan & Girgin (2020). In this study, the withdrawal strength tests of the four types of nails with annular/helical shanks and wood screw (self tapping screw) were executed on 200 CLT specimens of 50mmx50mmx100mm. Each single fastener was driven perpendicularly into the surface (side face) of CLT specimen via manual/gun drive as in the wall-floor angle bracket connections. Not only the numerical values of holding capacity but also the load-displacement curves are focused in the experimental tests. As a result, the phosphate coated annular nails among all the nail types have the highest efficiency due to the improved mechanic friction of rough crystalline coating as well as the resistance to outdoor damp conditions (Fig. 1). Furthermore, the withdrawal energy during the pull-out of single fastener, which is not investigated so far but may have highly significant implications for metal connections of CLT panels, was evaluated graphically. So higher withdrawal resistance and withdrawal energy of phosphate annular nails may lead to more economical and high-performance solutions for CLT connections in future applications.

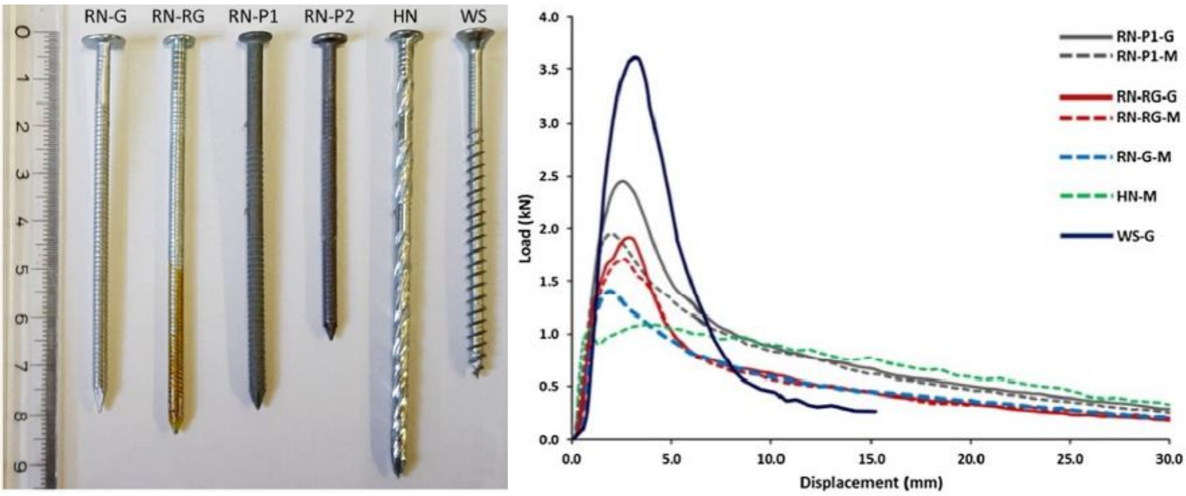
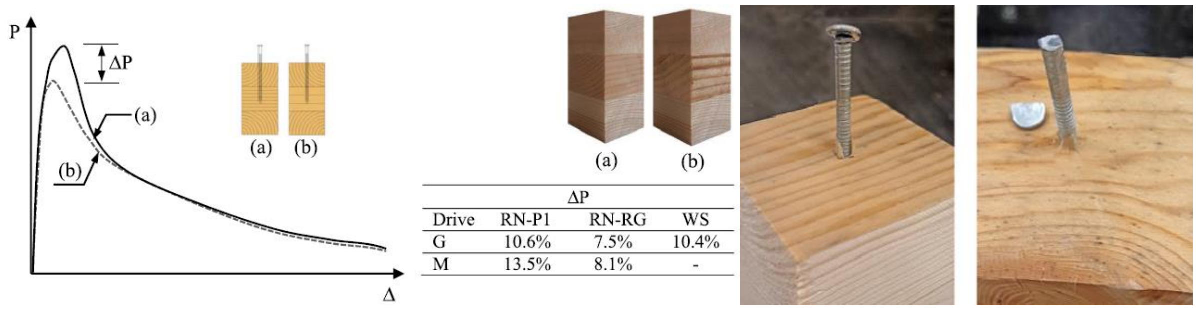


Figure 1: (a) Nail types and wood screw for withdrawal tests, (b) combined load–displacement curves for averaged of all fasteners (Ceylan & Girgin, 2020).

This study also draws attention to the difference caused by driving style (gun or manual) as well. The peak load in gun drive, comparing with manual one, indicates 25% increment for phosphate coated and 13% for galvanized+partially resin coated nails. In phosphate coated annular nails, for manual drive case, 40% improvement in holding capacity compared with common galvanized ones was realized from the experiments. For CLT specimens, the effect of pattern of growth rings with manual/gun drive option (Fig. 2a) not available in the literature are also partially discussed. In the experiments, particularly, inclined close-close-close grained layers were focused to minimize the uncertainties. It may be expected lower values in the range of 7.5–13.5% compared with close grained middle layer ones. Finally, it should be mentioned that some unexpected premature failure cases were observed. Head deformation in some galvanized annular nails and broken head in some resin coated annular nails (Fig. 2b) were observed.



ΔP			
Drive	RN-P1	RN-RG	WS
G	10.6%	7.5%	10.4%
M	13.5%	8.1%	-

Figure 2: (a) typical withdrawal load–displacement with respect to grain density and averaged differences, (b) unexpected failure modes in withdrawal tests (Ceylan & Girgin, 2020).

3. Experimental Investigation of CLT Wall-to-Floor Connection Deformation

In order to develop energy-absorbing CLT panel connections many experimental studies have been conducted on the effectiveness of the connections, especially for the earthquake prone regions. One of these researches, see (Ceylan & Girgin, 2019) was experimentally investigated the performance of a full-scale CLT wall-to-floor specimen assembled with metal connection under axial tensile force due to bending moments of seismic loads, after withdrawal tests of fasteners. Domestic angle bracket, plates, and phosphate coated annular ring nails were used in metal connection of the CLT panels.

All the displacements and strains were measured and collected during the test of the specimen, behaviour of connection and the failure modes (Figs. 3-4) was observed. As a result, the back side deformation of CLT wall member was prevented with the plates for a longer period compared with no-plate case and the withdrawal resistance of from CLT floor increased through phosphate coated annular ring nails and extra three nails in the corner of angle bracket on the front side. As a result of experimental tests it was concluded CLT panel connections can successfully dissipate energy with domestic angle brackets, plates and the type of phosphate coated annular nails fasteners. The results are promising, and the further experimental researches will continue for the most effective connection type.

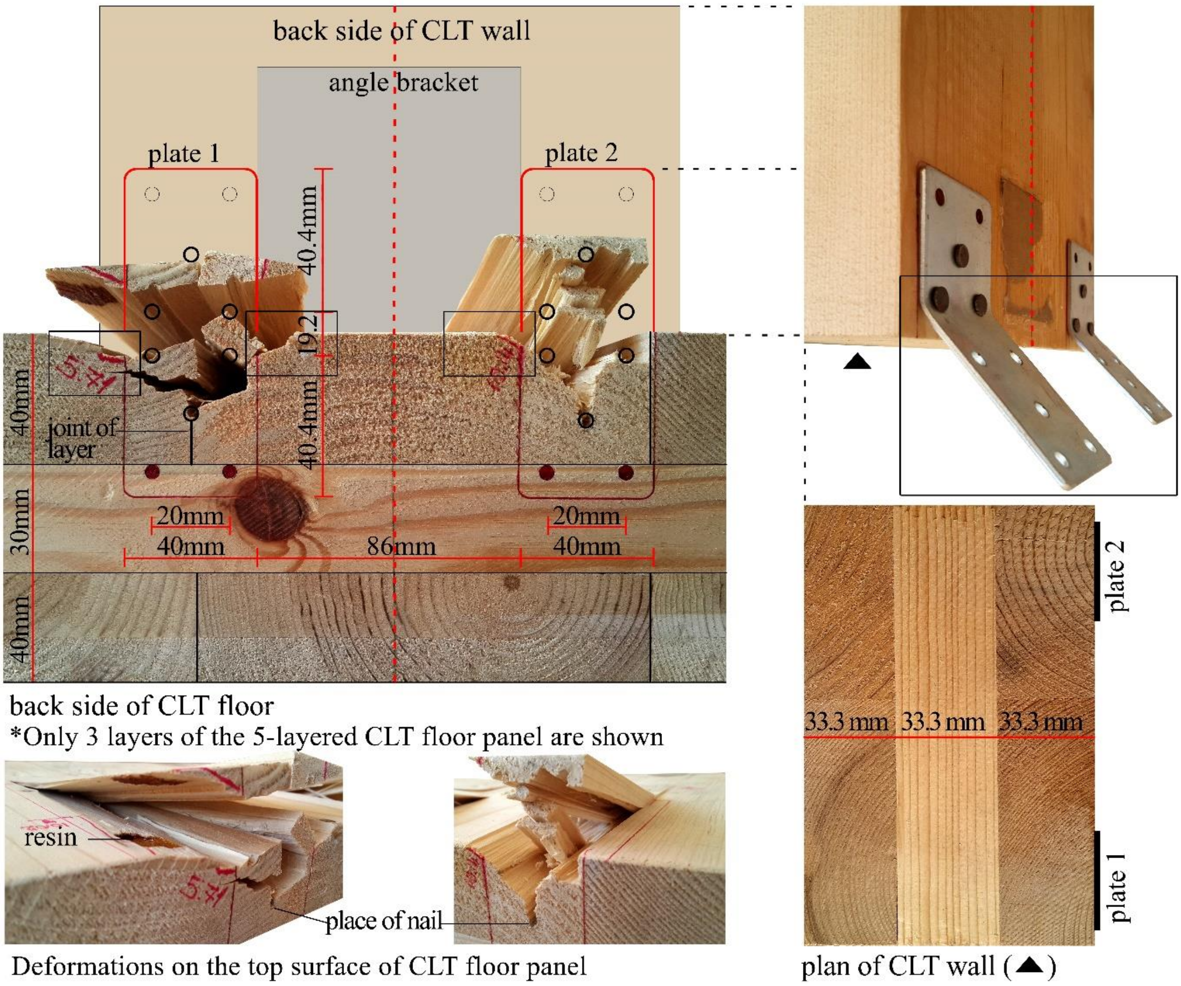


Figure 3: The back side deformation of CLT wall-to-floor connection (Ceylan & Girgin, 2019).

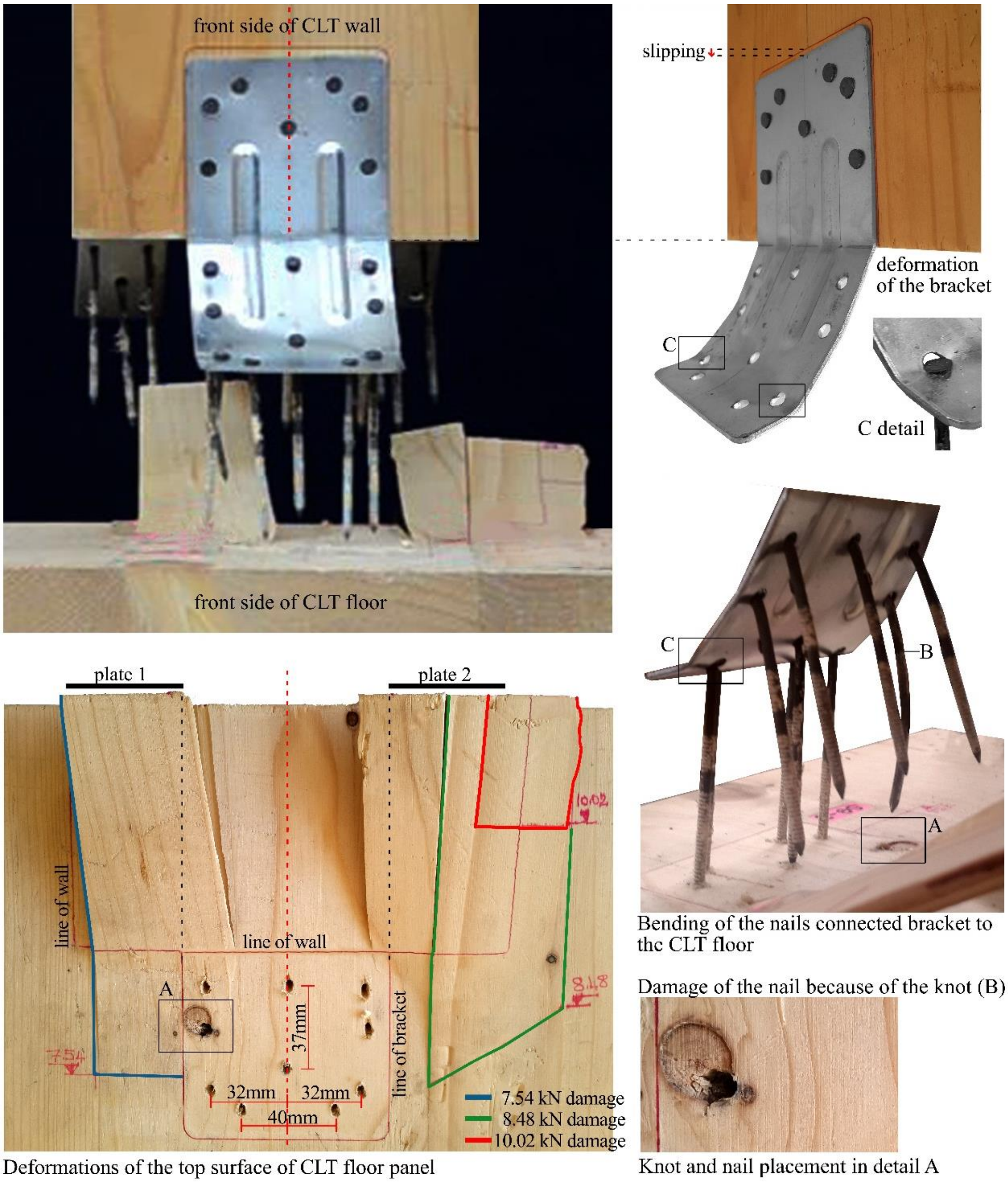


Figure 4: The front side deformation of CLT wall-to-floor connection (Ceylan & Girgin, 2019).

4. Conclusions and Future Work

This contribution provides a brief summary of the withdrawal resistance of various annular ring nails in CLT and ongoing research on the behaviour of CLT wall-to-floor connections under building loads. It is very important to carry out comprehensive research and experimental investigation on CLT connections to determine the behaviour and deformations. From this point of view, it is possible to develop building codes related to multi-story timber buildings by evaluating experimental results. Moreover to provide domestic timber with sustainable forest management for CLT panel production leads to improve forest asset as well as a positive contribution to the economy.

Creep behaviour of structural timber elements and considerations for mass timber construction

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1. Introduction

Timber as a structural material demonstrates many benefits over more commonly used structural materials. It is a naturally grown, aesthetically pleasing material with a high strength-to-weight ratio and has the added benefit of trees sequestrating carbon from the environment which is stored in the timber during its in-service life. Furthermore, in recent years, there has been a significant advance in engineered wood product technology and connection systems that have allowed timber to rival more commonly used structural materials and reach new heights, paving the way for environmentally friendly structures. When using timber as a structural material, particularly in bending, the behaviour is often not governed by its structural strength or ultimate limit state, but by the serviceability limit state, namely deformations and vibrations. As a result, careful consideration must be given to long-term performance which is often termed creep deformation. When subjected to loaded situations for long periods, timber is susceptible to creep strains or deformations, and for timber structures, the creep deflection can be large relative to the instantaneous deflection (see Figure 4). Three primary components contribute to the total creep deflection of a structural timber element. These three components are (i) time-dependent or viscoelastic creep, (ii) mechano-sorptive creep due to moisture changes and (iii) pseudo-creep that is attributed to swelling and shrinkage of the timber.

Figure 4: Creep deflection of timber beams subjected to a sheltered external climate (credit: Martin Ansell, University of Bath).

Viscoelastic creep in wood is described as additional strain with time at constant moisture content and constant environmental conditions under sustained loading. This additional strain manifests as an increase in deflection when subjected to bending. Timber and creep in timber are also heavily influenced by the surrounding environment. Under changing relative humidity, hygro-expansion or swelling/shrinkage deformations of wood must be considered but also, under load, the creep behaviour of wood is accelerated with changing relative humidity. This behaviour is known as mechano-sorptive creep behaviour and is a strain/deformation due to an interaction between stress and moisture content change in wood. Typically, there is an increase in the deflection during each drying phase and a decrease during the wetting phase of a relative humidity cycle. In a variable climate, the total strain/deformation comprises the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components. The typical behaviour can be observed in Fig. 2, whereby the mean creep deflection of a series of glued laminated beams over a 75-week period can be observed (O'Ceallaigh, 2016). Group UC is subjected to four-point bending in a constant climate with a relative humidity of 65% ± 5% and a temperature of 20°C ± 2°C and experiences an initial elastic deflection when loaded followed by viscoelastic creep with time. Group UV is also subjected to four-point bending but in a variable climate cycling between a relative humidity of 65% and 90% ± 5% with a cycle length of 8 weeks. It can be seen that the creep deflection is significantly greater when subjected to a variable climate as the deflection behaviour comprises the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components.

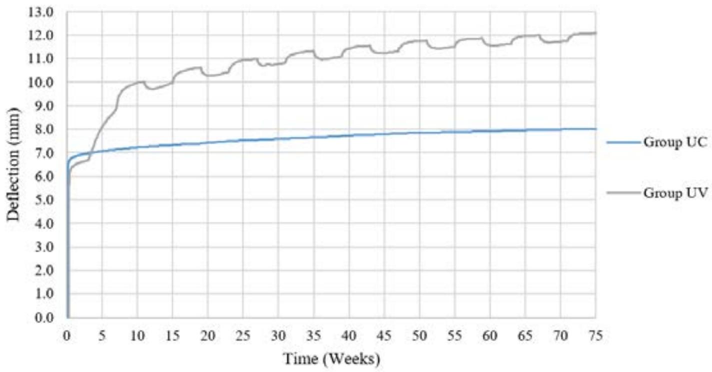

Figure 5: Mean creep behaviour of beams (Group UC) in a constant climate with a relative humidity of 65% ± 5% and a temperature of 20°C ± 2°C compared to beams (Group UV) in a variable climate cycling between a relative humidity of 65% and 90% ± 5% with a cycle length of 8 weeks (O'Ceallaigh, 2016).

2. Creep behaviour of Engineered Wood Products

2.1. Background

It is difficult to separate and characterise the individual creep components as they often occur simultaneously within a loaded structural element in practice. In the design of such structural elements, factors are available that account for additional deflections with time. Eurocode 5 provides deformation modification factors or k_{def} factors which account for creep effects with time. The k_{def} factor is used to increase the initial elastic deflection of the designed element. These factors are dependent on the type of timber product (solid timber, glued laminated etc.) and the different service class conditions in which the product will be used. The recent developments in mass-timber products such as cross-laminated timber (CLT) and the associated connection systems have resulted in a rise in the use of timber in medium to high-rise structures. While the technology is well established, there has yet to be a building that has withstood the test of time to correctly examine if current design guidelines for the calculation of creep are appropriate for CLT under the increasing structural demands of modern construction. While creep modification factors are well established for products such as solid timber and glued laminated timber, there are currently no specified k_{def} factors for CLT in Eurocode 5. Instead, the specification of modification factors or k_{def} factors for CLT is specified by the product manufacturers within their respective European Technical Approvals (ETAs). The following section examines some of the most significant studies that have attempted to accurately characterise the k_{def} factors for CLT.

2.2. Experimental and Numerical Modelling Activities

The following studies have performed state-of-the-art research activities to determine and aid the development of design guidelines for the safe prediction of long-term or creep effects in engineered wood products. It is important to note that there have been a significant amount of studies that have examined the creep behaviour of timber under several different climates and service class conditions and these form the basis for our current design standards in Eurocode 5. There is, however, limited experimental information on the creep behaviour of modern engineered wood products such as CLT (Binder et al. 2022). Some of the most significant studies to date have been performed by Jöbstl & Schickhofer, (2007) and Unterwieser & Schickhofer, (2013) where CLT was subjected to experimental creep testing. Jöbstl & Schickhofer, (2007) examined both CLT and glulam elements under constant climate conditions and common load levels and demonstrated that greater creep deflection was observed for CLT but the influence of creep in transverse layers subjected to rolling shear can contribute significantly to this increased creep behaviour. Colling, (2014) indicated that creep in transverse layers could be significantly higher than that parallel to the grain, potentially by a factor of 10. Jöbstl & Schickhofer, (2007) also observed a dependence on the number of layers and proposed k_{def} factors depending on the number of layers with panels of seven layers or less being subjected to a factor of 1.1 or an increase of 10%. Building upon the work, Unterwieser & Schickhofer, (2013) highlights that CLT should potentially be assigned with similar creep modification factors to that of plywood (CEN, 2005) with no allowable creep modification factor for Service Class 3 conditions. It is also worth noting that creep behaviour in timber is significantly influenced by stress and the comparisons between glulam and CLT at common load levels may result in significant differences in stress levels and make comparisons difficult. However, it is apparent that the influence of rolling shear in transverse layers cannot be ignored.

The current consensus by a series of product manufacturers is that k_{def} factors of CLT should be comparable to that of solid timber, glued laminated timber and laminated veneer lumber and this is specified in many ETAs. Some European National Annexes are also in agreement with this but these values are not in agreement with the research reported above. At the time of writing, the k_{def} factors for CLT of 0.8 for Service Class 1 and 1.0 for Service Class 2 have been proposed in the most recent draft rules submitted to CEN TC 250/SC 5 for the next generation of Eurocode 5. This is a conservative approach based on the current experimental data and evidence available. It is expected that CLT will not be specified for Service Class 3 conditions and is solely limited to Service Class 1 and Service Class 2 conditions as is currently the norm.

The availability of long-term experimental data is a concern for the industry but there has been a significant effort to utilise finite element modelling to predict this behaviour over longer periods of time. Timber is a challenging material to model numerically due to its natural variability in properties and anisotropic behaviour; however, in recent years, timber has been modelled successfully under long-term loading situations thereby increasing the reliability and safety of structural timber design. The recent advances in the modelling of the creep behaviour of timber by O'Ceallaigh et al. (2020), Hanhijärvi & Mackenzie-Helnwein (2003) and Fortino et al. (2009) have resulted in validated fully coupled three-dimensional moisture-displacement models that can be used to predict the long-term behaviour of timber elements under varying climates and relative humidity conditions. Experimental monitoring of the long-term behaviour of engineered wood products is a costly and time-consuming process and the benefits of a validated model will provide a powerful tool to aid the further development of such engineered wood products in the future. This is coupled with a significant effort around the world to instrument and monitor some of the many demonstrator structures using CLT and novel mass timber solutions (Riggio & Dilmaghani, 2019; Schmidt & Riggio, 2019). Other studies monitoring elements such as CLT shear walls and Timber Concrete Composite (TCC) beams are also being successfully utilised in a number of structures as novel solutions to examine the deformation performance and the vibration criteria. Similar numerical studies of this technology were analysed by Fragiacomo & Ceccotti, (2006) and Binder et al., (2022) with modelling efforts proving successful. Fragiacomo & Ceccotti, (2006) developed a validated model based on two long-term experimental tests in outdoor conditions. Despite some uncertainties in environmental conditions and material properties, a good fit between experimental and numerical results was obtained. Binder et al., (2022) examined and compared TCC and CLT panels and demonstrated similar creep behaviour after a 50-year design life based on a numerical study.

It is clear that the use of CLT and mass timber solutions in construction will continue and there is still a significant opportunity to examine its long-term performance through experimental testing, instrumentation of in-situ elements and numerical activities in the future to further improve the safety and reliability of structural timber design.

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WG2.SG2 – Vibrations

Definitions for vibration issues in taller timber buildings

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There are several classification criteria for vibration problems in timber engineering based on the excitation sources, the structural components and the ranges of frequency excitation. Concerning the sources of excitation:

- Ambient vibration
- Forced vibrations

Within forced vibrations, there are several excitation sources:

- Human-induced
- Wind-induced
- Seismic-induced
- Machinery-induced
- Blast

For the structural elements:

- Sub-components (e.g., beams)
- Floors
- Buildings
- Frequency of excitation:
- White noise
- Low-frequency
- High-frequency

As such, a state of art analysis is summarized in the following chapters, to collect major research contributions and open gaps on some of the above listed aspect.

Sub-components and vibration issues

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The main problems related to the vibration of sub-components are associated to the mechanical characterization of mass timber elements or engineering wood products and the acoustic performance of non-structural components. Experimental analysis, in this regard, is of primary importance for mechanical characterization. Besides, literature data are still relatively limited in number and further research efforts are needed.

In the same way, the assessment of the stiffness of joints is essential for the joints' design, monitoring the condition of building structures and prognosis of the lifetime and safety of buildings or their elements (Serdjuks et al., 2022a). Typically, such assessment is done in a non-destructive way using either shock or vibration analysis with a network of accelerometers as sensors.

Serdjuks et al. (2022b), more precisely, developed a non-model vibration analysis method and measurement system. It is based on the correlation principle of normalized coaxial accelerations measured in 3D space. The method is based on the mathematical analysis of vibrations of structural joints in 3 spatial directions using 3D accelerometers located at different parts of a joint and orientated coaxially. The developed method for assessing the quality of structural joints includes the electronic system for testing and mathematical processing of the obtained data. The developed measuring device consisted of an electrodynamic actuator, two 3D accelerometers, a signals amplifier, an Arduino board for signals conversion and transfer, and a computer.

The correlation method was verified in a laboratory experiment using rigid, semi-rigid and pinned joints of timber beams. Stand with timber beams joined at right angles by steel plates and screws were fabricated and tested by static loading to confirm the present state of the joint. Timber beams with 150X50 mm solid sections made C18 strength class were used for the timber stand. The decrease of the joint's stiffness in the case of probable damages was modelled by the loosening of the steel screws. The stand was subjected to a vibration load provided by electrodynamics actuators fixed on one of the joint elements. This element was excited by a chirp signal in a frequency sweep range from 10 to 500 Hz, where the most prominent resonance of the stand was found. Acceleration responses were recorded by 3D accelerometers placed on the loaded and connected beams. Peak values of the cross-correlation function between the responses from the correspondingly orientated pairs of coaxial accelerometers were determined. It was shown that the difference between the peak values of the correlation functions obtained for the rigid, semi-rigid and hinge joints enabled specification of the joints' stiffness.

The use of new technologies, in view of meaningful non-destructive tests for mechanical characterization, is expected to offer a major contribution in the analysis, measure, diagnostic investigation of sub-components for taller timber buildings.

Floor vibrations in timber buildings

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1. Introduction

The scientific literature on this theme is quite extensive. It spans from modelling approaches to validation of technical recommendations. It mainly focuses on two sources of excitation: ambient vibrations (used for dynamic tests) and human-induced vibrations.

Overall, major questions are should answer the following questions:

- Which is the approximation in estimating the modal parameters using simplified methods, as recommended in the standards? Experimental tests and modelling attempts might have shed light on this issue.
- Which are the modelling approaches for human-induced loads. Are there any relevant findings from these studies that highlight an upgrade of the standards?
- Are there recent studies quantifying the level of discomfort of timber floors?
- Are there relevant researches on the floor's modelling?
- Any research on fatigue in timber floors (repetitive loads)?

The existing guidelines for timber floor vibrations typically assume that support conditions for floors can be considered as theoretical, pinned connection. In practice, however, the conditions can differ significantly from the assumption due to applied construction details (e.g., vibration isolation strips, flexible connectors, moment-resistant joints), imposed loads in the case of statically indeterminate systems (e.g. shrinkage-induced deformation in composite floors). This, in turn, can have significant effect on the vibration properties of the system, namely, natural frequencies, mode shapes and damping, compared to theoretical estimates. Consequently, this leads to uncertainties in the response evaluation of floors. Here, few publications related to the topic are summarised.

The study by (Jaaranen & Fink, 2022) deals with modal analysis and corresponding simulations of two-way timber-concrete composite floor. The results show that vertical flexibility of the supports as well as uplift in the corners can affect the mode shapes of the plate significantly. Furthermore, a model that could be used to further investigate the effects, is presented.

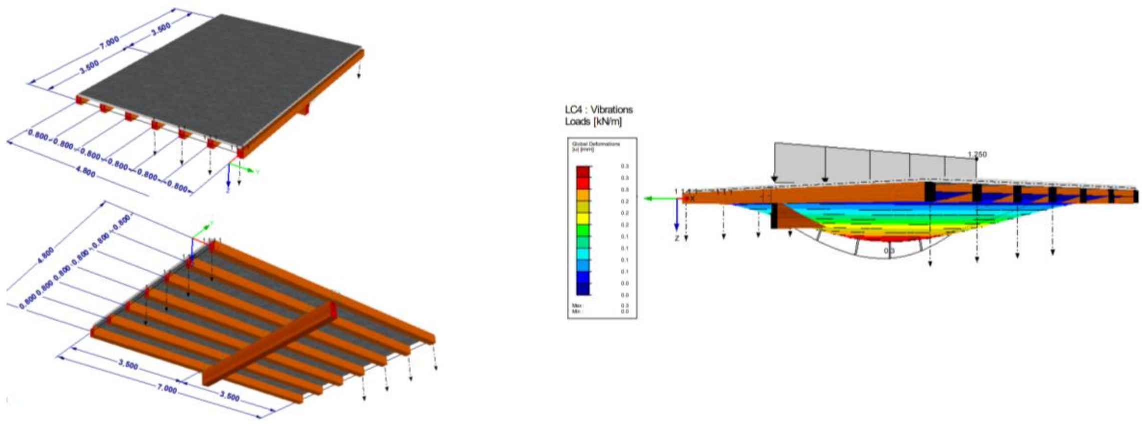
Jarnero et al. (2012) investigated the effects of different vibration damping interlayers on the modal properties of a prefabricated timber floor element, compared to typical simple supports. The results indicate that, as a common trend, the interlayers reduce natural frequencies but increase corresponding damping ratios. However, this trend is not fully consistent, and effects vary widely between different vibration modes; in some cases, even an opposite effect can be seen. The authors suggest that impulse velocity response of the floor is reduced by adding the interlayer.

Bolmsvik & Brandt (2013) compared the modal behaviour of two timber wall-floor assemblies: the floor is screwed or supported by elastomer interlayer. The trend was that use of the interlayer decreased natural frequency but increased damping. Furthermore, it was found that using the interlayer, the mean acceleration levels of the floor rose significantly for the frequencies below 40 Hz, which can have adverse effect on vibration comfort.

In his PhD thesis, Basaglia (2019) investigated experimentally the dynamic behaviour of a long-span ribbed-deck timber floor. The investigations showed a 15% decrease in the fundamental natural frequency by using a vibration isolation interlayer on supports. However, a striking increase of the damping ratio from 1% to 5-7% for two lowest modes was observed. It should be noted that this was one of many configurations with the isolation layer and not all of them displayed such a large increase. In the case with highest increase, the cause might be partially due to clamping effect induced by added weight on the supports.

Akter et al. (2021) studied the wall-to-floor-to-wall connections in platforms. Although a large portion of the paper concentrates in the moment-rotation behaviour of the connection, also effects of the connection to the floor deflections are discussed. In discussion, they suggest that moment-resistance of the joint can decrease static deflection of the floor up to 40%. The effect, however, depends widely on the thicknesses of used CLTs. Although their result considers only static behaviour, the use of these kinds connections is likely to have a pronounced effect on the floor vibration behaviour as well.

The TCC concept has been studied and developed over the past decades. The variety of solutions shows the meaningfulness and functionality of this system, as well as the continuous work of scientists over time (Skaare, 2013). To benefit from these advantages, the composite needs to provide sufficient stiffness to meet the serviceability criteria and load capacity to resist loading at every stage of the building life (Stepinac et al., 2020; Perkovic et al., 2021, see Fig. 1).



(a) (b)

Figure 1: Example of (a) structural system and (b) deflection-stiffness design. Reproduced from (Perkovic et al., 2022) under the terms and conditions of a Creative Commons CC-BY license agreement, November 2022.

An example of connector types and load slip curves according to EN 1995 is given. This paper discusses possible limitations related to residential areas, and additionally, the possible solutions that EN 1995 does not discuss in the case of resonant response (f1 < 8 Hz). The theoretical studies were accompanied by numerical analyses considering certain simplifications suitable for practical use (Santos et al., 2015). Numerical modelling is a powerful tool aimed at expanding knowledge and saving time and, ultimately, finance. Efficient data input and intuitive handling facilitate the modelling of simple and large structures. The numerical analyses aimed to extend the knowledge of the behaviour of the tested system. Furthermore, the numerical simulations served to confirm and complement the experimental results. In this paper, the RFEM pro-gram is used, a powerful 3D FEA program helping structural engineers meet requirements in modern civil engineering. One such case is certainly composite systems, specifically, timber–concrete systems. An additional aggravating circumstance is defining and calculating a semi-rigid connection between the different elements and materials. There are several options to calculate a semi-rigid composite beam or floor. The main difference is in the modelling method itself. Some methods ensure simple modelling (such as the gamma method). However, there are other more complex methods (shear analogy). Another option for modelling a composite system is shown in this paper. Since the definition and analysis of connecting elements are time-consuming, it is recommended to connect the surfaces of the elements to the other surfaces directly. Although there are several options in this software, the coupling member surface with the line release option will be shown below. This work was intended to research TCC systems and their applications while focusing on FEM analysis and vibration performance of standard TCC systems in residential and office buildings, and potential problems that may occur related to vibration design. In addition to the proposed models for the calculation of vibration, velocity, and acceleration, analytical models for calculating different types of slip modulus are given. This is an important detail because the degree of coupling conditions the stiffness of the system and, thus, the vibration conditions themselves. The composite timber–concrete system is an efficient system that is applicable during new construction or restoration, and consists of a monolithic concrete slab connected to timber beams. Comparing the load-bearing capacity of this composite system with the load-bearing capacity of the constituent elements, it can be concluded that the system has up to four times higher stiffness and up to twice the load-bearing capacity. For wide-span ceilings, the vibration design is often governing. The advantage of the lighter material of timber over concrete becomes a disadvantage, be-cause a high mass material is advantageous for a low natural frequency. Having long stiff support beams and shorter floor spans can ensure improved vibration performance when compared to systems with longer floor spans and shorter beam spans. An assessment and calculation of the TCC system was made, which was satisfactory for the frequency, additional acceleration, and stiffness limit criterion. Finally, FE analysis showed that stresses occur locally within the connector area in the concrete slab on both sides of the joint. The advantages of TCC (vs. sole timber) that can be emphasized are increased stiffness through composite action, increased floor mass at decking level, improved sound insulation (airborne sound), and reduced sensitivity concerning vibrations. If, on the other hand, the TCC is compared with pure concrete, it can be concluded that the weight is reduced, the CO2 emissions are reduced, the building process is faster, and reduced effort is needed for the props and formwork.

2. Comfort analysis

As part of the research work carried out by the Working Group 3 of COST Action FP0702, the need for vibrational comfort design for buildings and current regulations for comfort assessment of structural vibrations of timber floors in Europe have been summarised. Also, the design practices of timber floors with respect to vibrational serviceability criteria, including those for fundamental frequency, unit point load deflection and unit impulse velocity, in up to thirteen European countries have been gathered and their differences been further assessed by analysing flooring systems constructed with three types of joists, i.e., solid timber joists, engineered I-joists and metal web joists. The unit point load deflection criterion is the most crucial one for structural design of timber floors with various types of joists and usually dominates the whole design (Zhang et al., 2013).

Kowalska-Koczwara et al. (2018) presented selected aspects of the influence of urban transport vibrations on humans in buildings. The first analysed issue was the influence of the type of source of transport vibrations on the results. The analysis shows that the excitation caused by the passage of light-wheeled vehicles has a more negligible impact on the perception of human vibrations than the vibrations caused by heavy rail vehicles. Next, the authors determine the relationship between the human perception vibration ratio (HPVR) and the vibration dose value (VDV) for individual dynamical events. Finally, a significant and practical result of the work was to determine the zone of the possible location of the measurement sensor used to evaluate the influence of vibrations on people in buildings. Kreis (2021) investigated the vibration of two-Way Spanning Timber-Concrete Composite Slabs made of Beech Laminated Veneer Lumber with Steel Tube Connection.

Timber buildings and vibrations – Operational Modal Analysis aspects

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Timber buildings are prone to high-level vibrations, which is related to possible discomfort to the occupants (ambient vibrations). Additionally, the dynamic properties are important to predict their response under seismic and wind-induced vibrations.

The dynamic response depends on the amplitude of the excitation. The low-amplitude excitation has been investigated from experimental tests and model updating. The high-amplitude excitation is significant to understand possible nonlinearities of the response in terms of modal parameters. The damping, in particular, is extremely relevant for earthquake engineering. Are there researches which estimate the damping from high-amplitude tests (shake-table tests)? The participants should collect and organize the main findings on this topic, from ambient tests, continuous dynamic monitoring, shake table tests? Do the environmental parameters (i.e., temperature, relative humidity) significantly affect the dynamic response? (continuous dynamic monitoring). Is timber vibration a limitation for tall buildings?

Even though the popularity of timber structures has grown a lot during recent years, the engineering knowledge concerning the dynamic behaviour of tall timber buildings is still limited (Abrahamsen et al., 2020; Fig. 1). In taller, more slender and flexible timber buildings, serviceability considerations associated with lateral movement assume increased importance compared to low-rise buildings, where strength is usually the governing design criterion. For instance, the wind-imposed forces on a tall and slender building, while they may not damage any structural element, may cause deformation or vibration in the building which could cause discomfort to occupants, damage non-structural elements, or otherwise prevent the normal operation of the building. Both recent technological developments and increased use of engineered wood products reflect in deficiency of current timber codes and lack of knowledge by professional engineers. As engineers strive to take multi-storey timber buildings to new heights, it is necessary to understand how existing buildings, and current construction systems, are behaving in-service, and how their performance relates to what predicted at the design stage. A better understanding of the dynamic behaviour of mid-rise and high-rise timber buildings is of paramount importance in order to design future buildings more efficiently.

Figure 1: Structure of the Treed-It building (concrete core, glulam structure). Figure by ©Abrahamsen et al. (2020).

Probably the first ambient vibration tests (AVT) on a timber-frame building were performed by Ellis & Bougard (2001). The tests were conducted on a full-size, six-storey timber framed structure constructed inside BRE's Cardington laboratory. They performed both Forced Vibration Tests and Ambient Vibration Tests at different stages of construction, which allowed to evaluate the contribution to the global stiffness of the timber frame alone, the contribution of the staircase, and that of the finishing and cladding (bricks). The results of their research indicate that the building's non-structural components play a large role in the contribution to the lateral stiffness of the building at service levels. More recently, some other researchers have attempted to extract the modal properties of mid-rise timber buildings (Reynolds et al., 2011; Feldmann et al., 2016) using OMA methods. The research conducted by Reynolds and colleagues constitutes probably the largest database of AVT performed on timber structures in Europe to date. They tested different types of timber structural archetype: post and beam, timber-framed, pure CLT and hybrid timber-concrete structures. It is also worth to mention the tests performed in Germany and Austria on eight timber observation towers (with a height up to 45m), a 100m tall wind turbine and on three multi-storey residential timber buildings (with a height up to 26m). The findings of all these testing campaigns have allowed to assess the simplified relationship between height and natural frequency for multi-storey buildings given in Eurocode 1.

In North America, where there is a great tradition in wooden frame housing, efforts have been made to understand the dynamic behaviour of smaller low-rise residential buildings. Filiatrault et al. (2002) performed FVT using shake-table testing and highlighted the highly non-linear response of timber framed shear-walls to the amplitude of the excitation and motion induced by FVT. More recently, in Canada, researchers from FPI innovation, and in the U.S. researchers from Oregon University, have tested multistorey residential and commercial timber structures, up to six storeys, using OMA methods. The results of these campaigns have shed some light on the dynamic behaviour of tall timber buildings providing viable information concerning stiffness and damping of the tested structures to designers and stakeholders (Tulebekova et al., 2022). It is the opinion of the author that monitoring mid-rise and high-rise timber structures represents a big opportunity for the whole branch. This will aid in learning important lessons and enhance the confidence of the engineering community towards the use of this material.

Buildings and wind induced vibrations

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As the tall timber buildings are relatively new type of building, their horizontal vibration behaviour is not as well-known as it is for tall steel and concrete buildings. As mentioned, their lower mass and stiffness makes them more prone to wind-induced vibration problems. Few additional differences are that timber connection are often relatively flexible and soundproofing often requires use of flexible vibration isolation layers between storeys. Furthermore, due to lower stiffness of timber, non-structural components can have significantly higher overall stiffening effect in timber buildings compared to steel or concrete buildings. If these additional flexibilities and stiffnesses are not accounted for, it can lead to significant inaccuracies in modelling.

Furthermore, damping is likely affected by these details, and further understanding of their effects would be beneficial for designing more efficient tall timber buildings. Here, few publications related to the topic, although not covering everything, are summarised.

Talja & Fülöp (2016) summarize Eurocode design for wind-induced vibration and presenting some considerations for CLT buildings. In (Tulebekova et al., 2022), the authors investigate the effects of connection flexibility and non-structural components to the wind-induced vibration behaviour of an existing, tall GLT-framed timber building. For the purpose, a detailed finite element model, including non-structural elements, was established (Fig. 1).

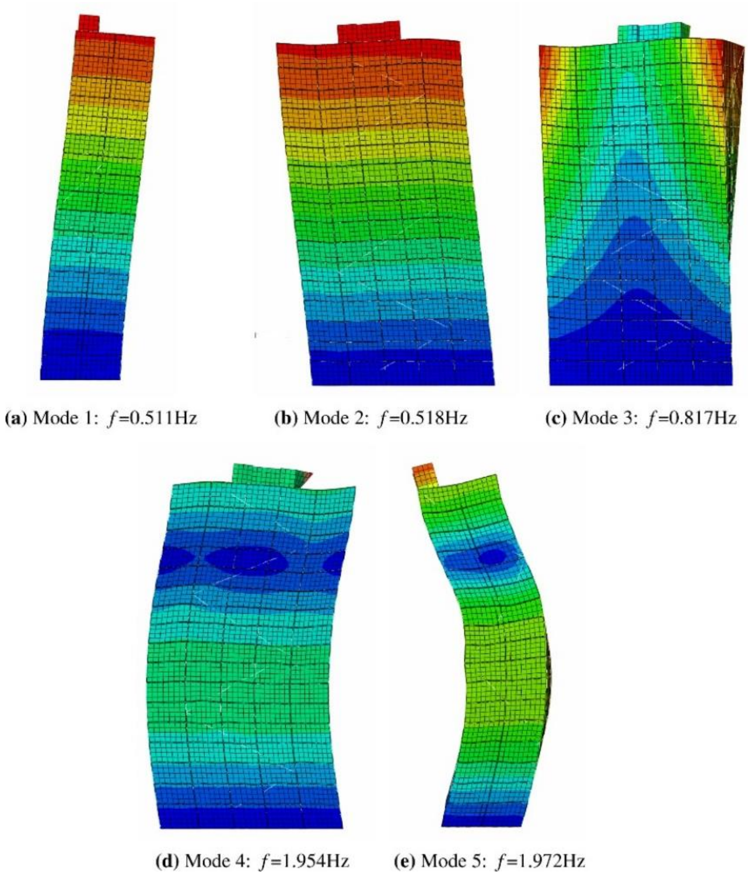

Figure 1: Numerical mode shapes after model updating for the tall timber building. Reproduced from (Tulebekova et al., 2022) with permission from Elsevier®, under the terms and conditions of a Creative Commons CC-BY license agreement, November 2022.

Flexibility of the connections was accounted for by introducing “connection-zones”, of whose stiffness could be adjusted by reducing their cross-sectional dimensions. The connection stiffness parameters were set by calibrating the model against experimental modal parameters from in-situ ambient vibration measurements. The main findings were that natural frequencies were sensitive to connection stiffnesses, especially the axial ones, and the mode shapes were significantly affected by the non-structural partitions, making these two factors important for accurate modelling of the building vibrations.

Reynolds et al. (2016) carried out ambient vibration measurement of 11 timber buildings of 10-49 meters high. Based on their investigations, the natural frequencies display a clear trend with respect to the building height. For damping, although some potential trends can be found, the scatter is very large. Furthermore, damping does not seem to clearly depend on the building type (timber-concrete, timber-steel or all timber).

Feldmann et al. (2016) presented a summary of ambient vibration measurements of 12 tall timber structures, including variety of towers and three residential buildings, with different structural systems. The reported results consist mainly of fundamental natural frequencies and damping ratios for these structures. The authors suggest the observed damping ratios are correlated to mass-ratios of different construction materials, used structural solutions and vibration amplitudes to some degree.

The role of connections on vibration issues

Angelo Aloisio, University of L'Aquila (Italy); **Chiara Bedon**, University of Trieste (Italy); **Thomas Reynolds**, University of Edinburgh (United Kingdom)

The exploration of high-amplitude dynamic response of Cross Laminated Timber (CLT) buildings has been the objective of several studies in recent years (Aloisio et al., 2020a; Aloisio et al., 2021; Mugabo et al., 2019; Reynolds et al., 2015). Experimental tests and numerical modelling conducted at the wall and building level proved that the major deformation contribution during the dynamic response of CLT structures depends on the joints and mechanical connections (Ussher et al., 2017; Weckendorf et al., 2016), see Fig. 1. Therefore, the dynamic response of CLT buildings can be distinguished in two phases (Ussher et al., 2022).

In the first level, under low-level excitation, the connections do not activate and the building behaves as an elastic continuum. In the second phase, under higher-level excitation, the connections activate, the global structural stiffness reduces and consequently a reduction in the natural frequencies of the building can be observed.

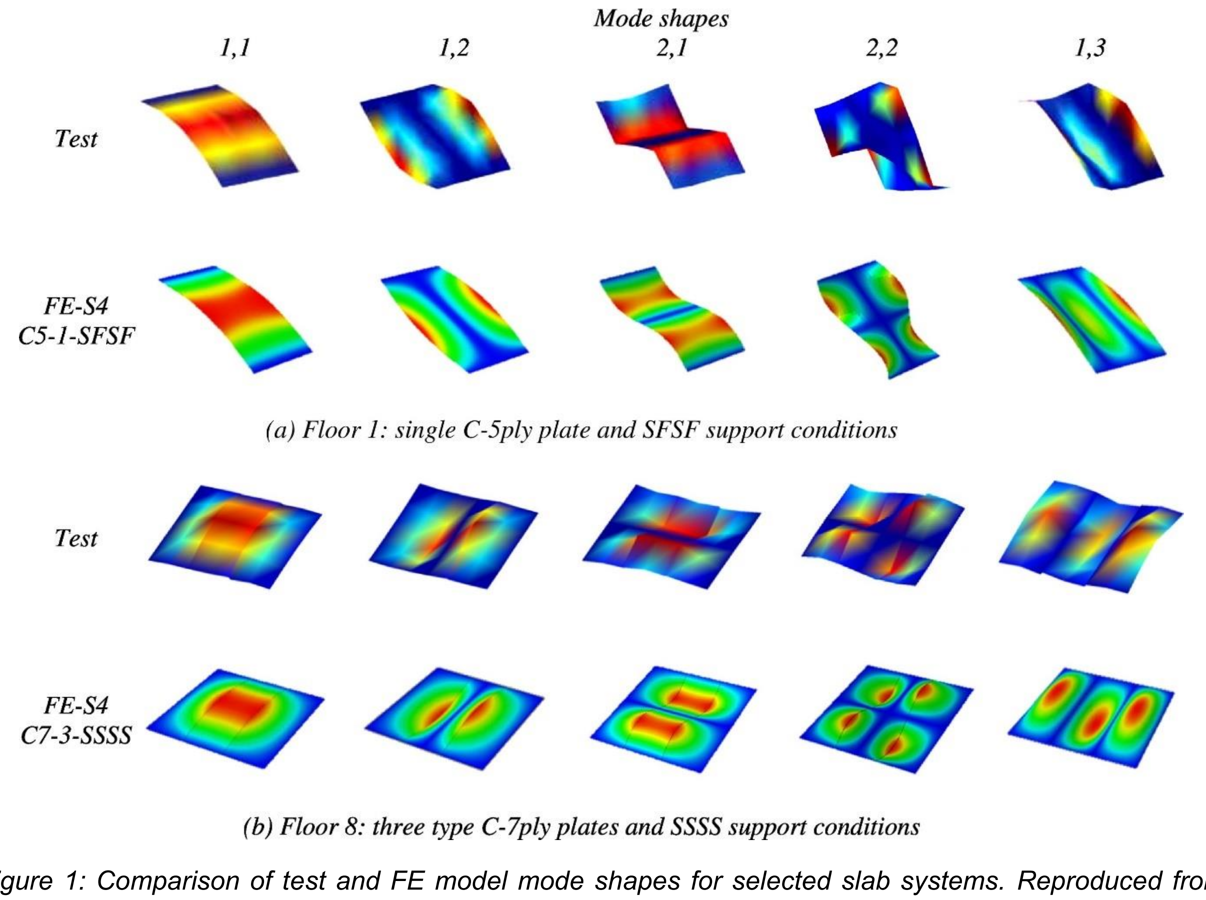

Figure 1: Comparison of test and FE model mode shapes for selected slab systems. Reproduced from (Ussher et al., 2017) with permission from Elsevier®, license agreement 5420840313461, November 2022.

This phenomenon is crucial in seismic engineering to carry out linear dynamic analyses. The practitioner must assume an estimate of the first natural period of the CLT building. However, its variability due to nonlinear phenomena challenges the scholar in choosing empirical expressions for predicting the natural period of CLT buildings.

Casagrande et al. (2021) observed three regions in the dynamic response of CLT: "no rocking," "partial rocking," and "full rocking regions." They measured a 3.7%, 11.2%, and 18.7% decrement of the natural period for one, three, and five-story shear walls, respectively. Parallelly, ambient vibration tests on CLT buildings showed that in operational conditions, the connections do not activate. Accordingly, CLT buildings are very stiff under low-excitation level.

Kurent noticed that CLT floors in CLT buildings behave like rigid diaphragms, in line with research by (Aloisio et al., 2020b) where they concluded that the CLT floors behave like rigid diaphragms for the fundamental modes. Additionally, Aloisio et al. observed that the estimated empirical formulation for predicting the first natural period of CLT buildings in operational condition is similar to the one used for masonry structures according to Italian technical codes. Interestingly, Kurent et al. (2021) showed that the wall-floor joints influence the vertical in-plane stiffness of the shear walls, which is reflected mainly for the lowest modes.

Vibrations and acoustic aspects

Angelo Aloisio, University of L'Aquila (Italy); **Chiara Bedon**, University of Trieste (Italy); **Thomas Reynolds**, University of Edinburgh (United Kingdom)

The EU Environmental Noise Directive of 2002 specifically addresses the prevention of environmental noise pollution. The Directive applies to noise to which humans are exposed, particularly in built-up areas. In 2008, the directive was extended to apply to vibration treated as pollution (BS 6472). In the Directive, direct or the indirect influence of vibration, heat or noise in air, water, or the soil are considered pollution. Despite the Directive, both stimuli noise and vibration are not combined together in the context of sustainable indoor comfort. International and national standards mostly treat these factors separately. In the literature and relevant standards, the perception of vibration in buildings has been analysed and studied in depth over the past decades (BS 6841; ISO 2631-1). On the other hand, as suggested by many other authors, the main "discomfort" experienced in buildings seems to be related to a combined effect of noise and vibration. As a matter of fact, noise and vibration occur simultaneously in buildings and, even if the acoustical or vibrational thresholds meet legal or standard limits, their inhabitants nevertheless report annoyance (Nering et al., 2020), see also the experimental setup recalled in Fig. 1.

The evaluation of exposure to two simultaneous stimuli single event (e.g., train pass by) was proposed in work of Nering & Kowalska-Koczwara (2022), based on previous work of Howarth & Griffin (1991), where annoyance level was introduced. Acoustic issues are often representative one of the main problems for lightweight constructions (Fossén et al., 2008).

(a) (b)

Figure 1: Example of (a) microphone measurement position in the tested room, (b) 3-axis accelerometer test position.. Reproduced from (Nering et al., 2020) under the terms and conditions of a Creative Commons CC-BY license agreement, November 2022.

Typical annoying sounds are people talking, television and footsteps. Transmission between a "source room" and a "receiving room" can be airborne or structure borne. Sound energy can reach the "receiving room" through various transmission paths: the separating wall itself could radiates sound energy directly into the receiving room, the separating wall could transmit vibration to the adjacent walls, which in turn radiate energy into the receiving room, the side walls of the "source room could transmit vibrations to the separating wall or to side walls of the receiving room (ISO 12354-1). All sounds that propagate through propagation paths other than direct transmission through the separating wall or floor are called flanking sounds. It is essential to solve the problems of flanking transmission in order to handle the sound insulation. Flanking transmission can be reduced limiting the vibrations transmitted to the walls and floors in the source room, reducing the radiation of sound from the walls and floors of the receiving room and reducing the vibrations transmission from the elements of the source room to the elements of the receiving room (Ljunggren & Ågren, 2013).

The latter strategy requires a complete separation of the construction frameworks of the adjoining apartments from each other. Separation is often achieved using layer much softer than the timber of structural elements above and below the insert. In the vertical direction, the separation is accomplished using an elastic layer between overlapping walls and between floors and walls. However, the layer is subjected to the static load of the volumes above the layer. This means that stiff layers must be used in the lower part of high buildings, increasing coupling and thus worsening the sound insulation (Negreira et al., 2014; Reichelt et al., 2016). Additionally, to prevent acoustic bridges via connections, special soundproofed steel angle brackets have recently been developed, in which the rigid parts are elastically separated from one another using interlayers. Elastomers are frequently used at junctions so as to reduce low frequency noise. Common types include closed cellular polyurethane ("CCP") and mixed cellular polyurethane ("MCP"), see (Azinović et al., 2021). Since the choice of the most adequate properties for the material is of crucial importance, elastomers should be characterized defining Young's and shear moduli for varying load-frequencies. Admissible vertical loads that guarantee the maintenance of the insulating properties and permissible shear strain must also be defined. The coefficient of elastomers on timber can be estimated as $\mu \geq 0.5$ and therefore it is useful to take the load transmission capability of the elastic layers into account and design. Although separation, is an effective solution of the sound insulation problem, it is often not the easiest since there might be a conflict against the building's overall deformability and stability requirements. Therefore, elastic connection must be carefully designed in order to allow the structure to appropriately manage the horizontal wind and seismic loads.

The influence of flexible sound insulation layers on the seismic performance of cross laminated timber walls has been studied by (Azinović et al., 2021). According to the authors the bedding insulation layer under the wall led to only minor changes in the load-bearing capacity of the walls under lower vertical loads but the stiffness of the wall decreased to less than 40% that of the uninsulated wall, due to additional lateral deformations enabled by the insulation. Experiments confirmed that a higher vertical load substantially increases the load bearing capacity, as well as the stiffness of the shear wall, due to the associated increase in friction. The cyclic response of insulated steel angle brackets with inclined and perpendicular screws used for cross-laminated timber connections has been assessed by (Kržan & Azinović, 2021). The monotonic and cyclic tests on the CLT wall-to-floor connections highlighted that insulation under the angle bracket has a marginal influence on the load-bearing capacity; however, it significantly influences the stiffness characteristics resulting in a 22% and 45% reduction of the effective stiffness in pure shear and tensile loading respectively. The relative energy dissipation and equivalent viscous damping coefficient were lower for the insulated specimens than for the uninsulated specimens, but the difference decreases with increasing displacements and repeated cycles. Friction energy dissipation was found. Recently, De Santis & Fragiacomo (2021) proposed an analytical model for the stiffness prediction of screw connection with deformable interlayers. The authors found that for connections with screws inclined with respect to the sliding plane, the slip modulus decreases much slower than for connections with perpendicular screws as the thickness of the intermediate layer increases.

State of the Art on Vibration-based Structural Health Monitoring of tall timber buildings

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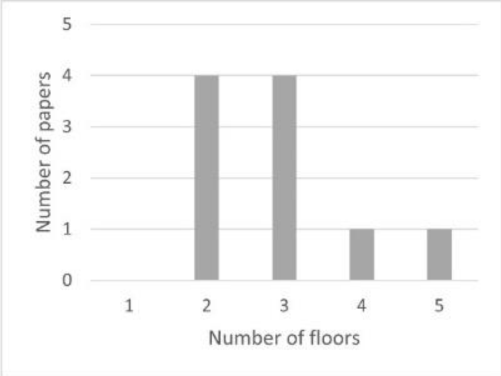
1. Introduction

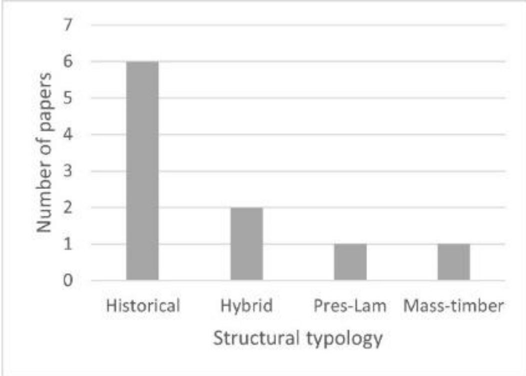
Vibration-based Structural Health Monitoring (VSHM) aims at tracking in time the dynamic properties of structures, such as modal frequencies, modal shapes, and damping factors, to identify changes in structural behaviour (Farrar & Worden, 2007). The rationale behind VSHM is that the dynamics of a structure depend on its stiffness, mass, and damping properties. Therefore, information about these variables, and their variation in time with respect to a reference condition, can be obtained by studying the evolution of the dynamic response of structures. Traditional VSHM systems are generally composed of hardware components, such as sensors (in general accelerometers), data acquisition systems, cables, transmission systems, and software aimed at processing data, extracting modal parameters and Damage-Sensitive Features (DSFs), and ultimately obtaining damage indices which alert about variations of DSFs between a reference (possibly undamaged) and current state of the structure. In the last decades, VSHM has been employed on different types of civil structures, such as bridges, buildings, damns, and stadia. Several examples can be found in the literature about long-term VSHM monitoring of concrete, metal, and masonry structures. Recently, few papers have been published on earth structures. Nevertheless, the literature on VSHM of tall timber buildings is still in its infancy. This short State of Art aims at providing a general overview of current literature on this topic, highlighting the different uses of VSHM information and specificities of timber in this field, as well as identifying future research needs and directions.

2. State of Art survey

The Scopus database is used to create a list of papers focusing on the topic of VSHM of timber structures (research carried out in October 2022). The list of papers is obtained considering the following keywords: “Timber” AND “building” AND “monitoring” AND ("vibration" OR "dynamic"). This research leads to 66 documents published between 2007 and 2022. For the sake of comparison, considering the keywords “concrete”, “steel”, and “masonry” instead of “timber” leads to 742 (published between 1979-2023), 498 (published between 1985-2023), and 311 (published between 1987-2023) documents, respectively. As for timber, considering only journal papers, the cluster reduces to 23 documents. Following, these documents are analysed one by one: 13 over 23 papers are excluded from the list since they are not available or are considered out of topic. Thus, only 10 papers are further analysed. Most of the case studies presented in these 10 papers relate to short timber buildings, e.g., with 2 or 3 floors, see Fig. 1(a). There are no papers dealing with tall buildings. As for the structural typology, a wide palette of different buildings and timber products is found. Most of the papers investigate the dynamic behaviour of historical buildings while only 4 papers deal with modern constructions, see Fig. 1(b). In turn, different types of modern timber buildings are studied, i.e., hybrid structures (e.g., timber + concrete), Pres-Lam buildings (unbonded post-tensioning tendons in beam-column connections), and mass-timber buildings. Regarding the use of vibration-based data, only three papers focus on the long-term monitoring of structures, while the remaining papers deal with the calibration of numerical models.



(a)



(b)

Figure 1: Outcome of the Scopus research.

3. Uses of VSHM information

The evaluation of the dynamic properties of timber buildings can be used for several purposes, such as damage identification, model calibration, and supporting the development of design codes and guidelines.

Damage identification. Damage, such as cracks and reduction of cross sections in structural members, can modify the stiffness of a structure and in turn its dynamic properties (Peeters & De Roeck, 2000). According to the number and location of sensors, the adopted SHM technique, and the types of models employed to describe the structure, different levels of damage identification can be attained. The traditional classification (Rytter, 1993) includes the following levels: (i) damage detection (alert about the existence of damage); (ii) damage localization (find the position of damage); (iii) damage quantification (assess the gravity of damage); (iv) damage prognosis (forecast the evolution of damage).

Model calibration. Modelling the stiffness of timber connection or the story stiffness can be challenging if not impossible in case experimental data are not available. This is especially true for historical constructions, which are generally affected by even higher uncertainty with respect to new structures. For instance, in (Lyu et al., 2017), experimental modal parameters are employed to calibrate a numerical model of a heritage Tibetan timber building. Ultimately, calibrated models can be used for structural assessment purposes.

Development of design codes and guidelines. Since tall timber buildings are relatively new on the construction landscape, the understanding of their behaviour is still limited in comparison with other types of structures. Expanding the knowledge on this type of structure will improve the confidence of designers and ultimately foster the diffusion of tall timber buildings (Ellis & Bougard, 2001). For instance, an important issue is understanding the dynamic behaviour of tall timber buildings under wind excitation to improve serviceability performances (Feldmann et al., 2016; Reynolds et al., 2011). Recently, in the realm of the DynaTTB research program (Abrahamsen et al., 2020), several dynamic tests are being carried out on tall timber buildings to improve the understating of damping properties of these structures and support the development of reliable Finite Element (FE) models.

4. Specificities of timber buildings

The dynamic properties of a structure do not vary only due to the occurrence of damage. Environmental and operational factors (EOFs) can modify the properties of healthy structures. This is a major concern in damage identification because of two reasons. First, EOFs might hamper the identification of structural anomalies. Second, variations in the dynamic behaviour due to EOFs might be erroneously attributed to damage. Therefore, the influence of EOFs on different materials and structural typologies must be carefully investigated. Extensive research on the effect of environmental factors, such as temperature and humidity, has been carried out on concrete, steel, and masonry structures, see e.g. (Magalhães et al., 2012). Operational factors extensively studied include, for instance, human actions and vehicular traffic, see e.g., (Hu et al., 2017). In the case of timber, EOFs are expected to strongly affect its dynamic behaviour. Nevertheless, the research on this topic is quite limited. In addition to temperature and humidity, which have been investigated extensively for other construction materials, one of the main concerns in the case of timber is its Moisture Content (MC). It influences several properties of timber, such as strength, density, and elastic modulus. In (Larsson et al., 2022), the relationship between environmental factors and the dynamic response of a hybrid timber-concrete building is investigated. To this purpose, modal parameters, i.e., modal frequencies, modal shapes, and damping ratios, are tracked continuously for three years together with hygrothermal parameters, i.e., temperature, relative humidity, absolute humidity, and moisture content. The results of the long-term monitoring show that modal frequencies change with the temperature, showing maximum and minimum values in early autumn and early spring, respectively. Instead, damping ratios do not present seasonal variations. As for the MC, it is observed that in addition to seasonal variations, the modal frequencies decrease in the first year after construction due to the drying out of timber elements. In (Granello & Palermo, 2020), the results of a 3-years monitoring campaign on a Pres-Lam building are presented. In this case, the results show that temperature and relative humidity as well as post-tensioning losses do not affect the dynamic behaviour of the structure.

5. Gaps to fill with research

Further research should be conducted in the field of VBMS of tall timber structures due to the lack of experimental data on real structures and knowledge about the structural performance of existing tall timber buildings. The general lack of data can be attributed to the low number of existing tall timber buildings and the - even lower - number of instrumented timber buildings or of experimental tests on full-scale buildings. The influence of EOFs should be better investigated, considering the great variability of timber materials and building typologies, especially hybrid structures. In addition, several timber products, such as cross-laminated timber, are relatively new materials, and their long-term behaviour is yet not known.

6. Conclusions

Despite the great interest in VSHM for civil structures, very limited applications exist in the field of tall timber structures. Despite the Scopus survey does not claim to be exhaustive, it shows that research on this topic is relatively recent and not very widespread, especially in comparison with other construction materials such as concrete and masonry. This is probably due to the limited application of this construction material, especially for tall buildings. Regarding the influence of environmental factors on the dynamic behaviour of timber structures, in the literature conflicting results can be found, probably depending on the large variation in the different timber construction typologies. Therefore, further research on VBMS of timber structures, and especially tall buildings, is recommended in terms of instrumenting more timber buildings and performing long-term monitoring campaigns on different typologies of timber buildings.

Current study on the influence of inter-panel connections on pedestrian-induced vibration of CLT floors

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With developments of new construction techniques and light yet high-strength building materials, vibration serviceability of floors due to pedestrian-induced loading has become a matter of growing concern in the civil engineering (Galbraith & Barton, 1970; Griffin, 1990; Racic et al., 2009; Sedlacek et al., 2006; Živanović et al., 2005). Moreover, the results of conducted experimental campaign (Hamm et al., 2010) showed that a large percent of timber floors that satisfy ultimate limit state design criteria fail to satisfy vibration serviceability assessment (VSA) norms. The influence of the inter-panel connections on both free and forced vibrations of CLT floors is often neglected in numerical modelling, treating a multi-panel floor as a monolith slab or with no inter-panel connections at all (Willford & Young, 2007; Erol & Sylvain, 2019; Eurocode 5). The research conducted within a current phase of Substrate4CLT project (Towards Sustainable Buildings) involves a number of numerical studies designed to examine the influence of the most common connection types on both vibration modes and responses of a range of different CLT floors due to pedestrian-induced loading. Although the connections are relatively complex, the current research involves a simple yet robust model suitable for both 2D and 3D finite element modelling of CLT floors, regardless the plate kinematic model, floor layout and considered walking paths. The model is based on findings of Paolini et al. (2017) and Macpherson et al. (2018). The Canadian CLT Handbook (Erol & Sylvain, 2019) warns that bare CLT floor systems differ from traditional lightweight wood joisted floors, thus the traditional methods and criteria for VSA of lightweight timber floors may not be applicable to CLT floors. Arup's design guideline for footfall-induced vibrations (Willford & Young, 2007), derived from a comprehensive database of recorded walking footfalls, offers a universal VSA framework that applies to any type of floor structure regardless of the material. Their so-called "vibration performance" approach to serviceability assessment advocates the evaluation of a vibration response level. This is radically different from the traditional approach of limiting the static deflection (w), the fundamental natural frequency (f) and comparing the w/f ratio to some prescribed values (Erol & Sylvain, 2019; Eurocode 5). The ongoing research project aims to study vibration levels of various CLT floors using Arup's model of walking loading, where the cut-off frequency between the low- and high-frequency floors is 10.5 Hz. Numerical simulations of various CLT floors carried out so-far showed that different modelling strategies for inter-panel connections provide considerably different modal properties and vibration responses. In case of no inter-panel connection, each panel behaves dynamically as an individual floor. Ideally, the connections would provide a rigid link between the panels, making no difference between a multi-panel floor and the monolith counterpart. In reality, the connections are far from rigid, so some differences in modal properties are expected. The differences in natural frequencies are the biggest for modes in which the modal coordinates are the largest along the connection line, i.e. when the connection line moves dominantly with respect to the rest of the floor. Moreover, the study suggests that the modal properties are more sensitive to the rotational stiffness of the connection than to the bending stiffness. The biggest differences between vibration simulations of the monolith floor and the floors with the panel connections were observed in cases when a pedestrian was walking along the connection line. This means that the connection lines should be kept away from critical walking paths or should be diverted by a clever arrangement of structural and non-structural elements, such as furniture and partition walls. Finally, the connections made a higher impact on the vibration performance of high-frequency floors than low-frequency floors. This is most likely due to fundamentally different nature of the two walking force models pertinent to the two floor types. Question arises which model should be used if a floor happens to have the fundamental frequency equal and even close to the cut-off 10.5Hz. A universal force model that would eliminate the need for the artificial division between low- and high-frequency floors is urgently needed for design of any type of floor regardless the material.

Future research should:

- estimate experimentally rotational, bending and shear stiffnesses of connections from dynamic tests on real CLT floors, to examine if their values are dependent on the vibration amplitude;
- include experimental vibration measurements of real floors which would evaluate more reliably the extent to which CLT floors with connections have different dynamic properties in comparison with how the VSA is carried out in current design practice.

Reduction of the floor deformation and vibration by rational use of timber-concrete composite instead CLT

Karina Buka-Vaivade, Riga Technical University (Latvia); **Dmitrijs Serdjuks**, Riga Technical University (Latvia); **Leonids Pakrastins**, Riga Technical University (Latvia)

1. Introduction

The trend toward using modular buildings in constructing multi-storey timber buildings leads to the need for large spans, which create more challenges in terms of long-term deformations and vibrations. Due to their low bending stiffness, conventional timber floor structures make it difficult to meet these requirements. In contrast, long-span floor structures are a potential field of application for timber-concrete composite (TCC). One of the most widely used structural solutions for timber-concrete composite slabs is the concrete layer with cross-laminated timber (CLT) slab (hereinafter CLT-concrete slab). So, the work aims to check the rationality of the proposed CLT-concrete slab as a floor structure for residential and office buildings compared with pure CLT slabs.

2. Materials and methods

For a more sustainable timber-concrete composite structure solution, the use of synthetic fibres instead steel reinforcement in the concrete layer is proposed (Aydin, 2013). A rigid connection between the fibre-reinforced concrete layer and the wood-base panel realised by the stone chips method (Buka-Vaivade & Serdjuks, 2022) is ensured. The comparison of the CLT-concrete slab and CLT slab is made for the most rational slab cross-sections, which require both ultimate and serviceability limit states. Due to different materials with different properties, especially in weight and price, material consumption cannot objectively characterise the rationality of timber-concrete composite structures. For the mutual comparison of structural solutions, a criterion of rationality has been introduced - the cost factor *c*, which links different types of materials in different variable proportions. The design of timber-concrete composite slabs is carried out by adapting the recommendations from the upcoming rules for timber-concrete composite structures and vibration. Both regulations – "Eurocode 5: Design of Timber Structures — Structural design of timber-concrete composite structures — Common rules and rules for buildings" and "Vibrations" are currently under development within the framework of CEN TC250/N2330 and CEN TC250/SC5 WG3 Subgroup 4. More about the used methodology and developed software for determining the most cost-effective cross-sections of the CLT and CLT-concrete slabs is described in (Buka-Vaivade et al., 2022). The most cost-effective cross-section parameters have been determined using developed software for spans from 3 to 8 meters with a step of 0.5 m at different categories of use and vibration quality classes. For the B category of use, the slabs are designed for 3 kN/m^2 distributed imposed load, for A – for 2 kN/m^2. For results cross-comparison, the total floor width used in the vibration checks is assumed to be 5 meters.

3. Results and discussions

The decisive check is on vibrations for CLT slabs, while for CLT-concrete slabs – ultimate deflections. Therefore, rational parameter values have been determined for CLT slabs at three possible vibration quality classes, but for CLT-concrete slabs only at a higher quality class. In Fig. 1, you can see the symbols used in the graphs in Fig. 2.

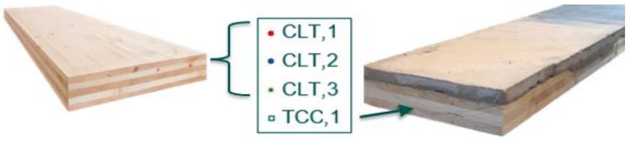

Figure 1: Used symbols for CLT and CLT-concrete (TCC) slabs. 1, 2 and 3 – vibration quality classes, respectively high, base and economic.

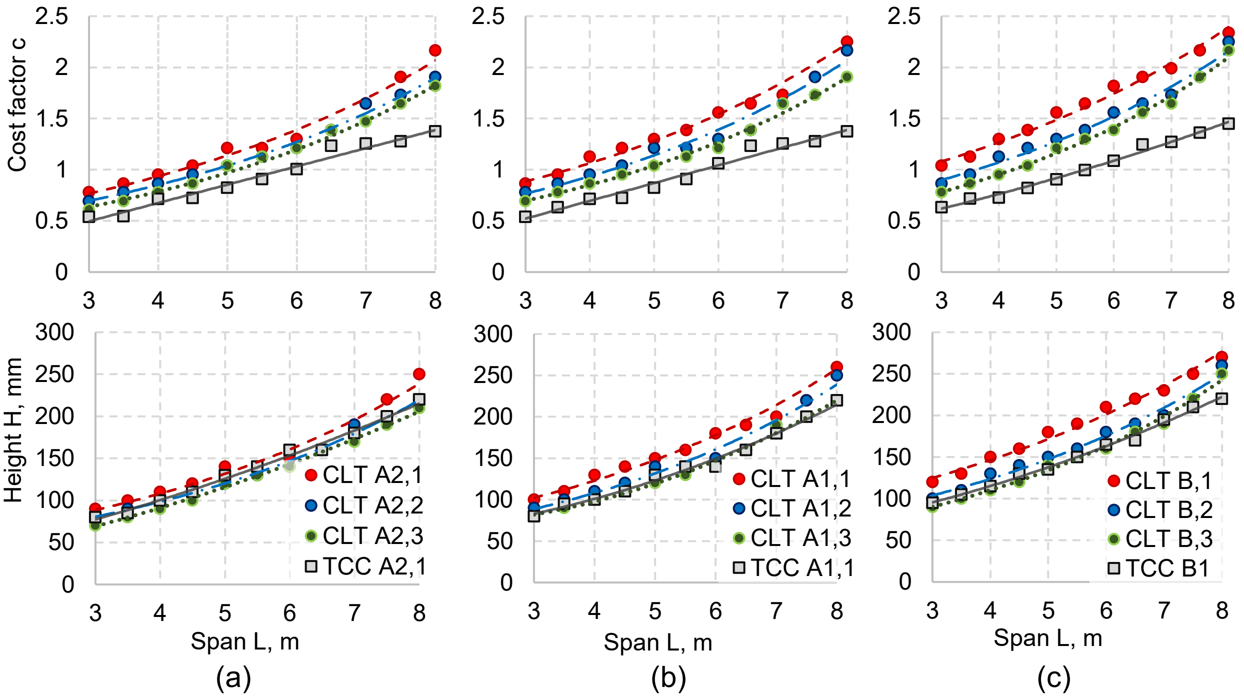

Figure 2: CLT and CLT-concrete (TCC) slab cost factor – slab span and slab height – span curves for the building category of use: a) A2; b) A1; c) B. 1, 2 and 3 – vibration quality classes, respectively high, base and economic, A2, A1 and B – single house, multi-storey residential, office areas.

The determined cost factor is based on the cost of the relevant cross-section material in the Latvian market in 2021/2022, at the turn of the year, for one square meter slab materials. But the developed software provides an opportunity to define the prices of the used materials according to the current situation in the building materials market. For CLT-concrete slabs, the thickness of the concrete layer varies from 20 mm to 85 mm. Such a concrete layer significantly improves the dynamic response of the structure. Summarising the results obtained in the calculations, the use of CLT-concrete slabs, compared to simple CLT slabs, is absolutely justified for the floors of multi-story residential buildings and office buildings at any selected vibration quality class. Such a solution can reduce the proposed rationality criterion - the cost factor in categories A1 and B by 22 % and 23 % on average. And it also almost does not increase the total height of the slab compared to simple CLT slabs that correspond to the economic (third) vibration quality class. In the case of single houses, CLT-concrete slabs can reduce the value of the cost factor by an average of 19 % compared to the most economical CLT slab solution. Still, simultaneously with the cost factor reduction, the slab's total height increases slightly by an average of 6 %. The percentage changes of CLT and CLT-concrete slabs cost factor *c* and total height *H* values compared to CLT slab parameters corresponding to 3, or economic vibration quality class, are summarised in Fig. 3. The benefit of using CLT-concrete in floor solutions increases with higher requirements for vibration quality class, larger spans and more busy areas. At the highest vibration quality class in office-type buildings, the structural solution of CLT-concrete can reduce the cost factor by up to 44 % and the slab height by up to 25 %.

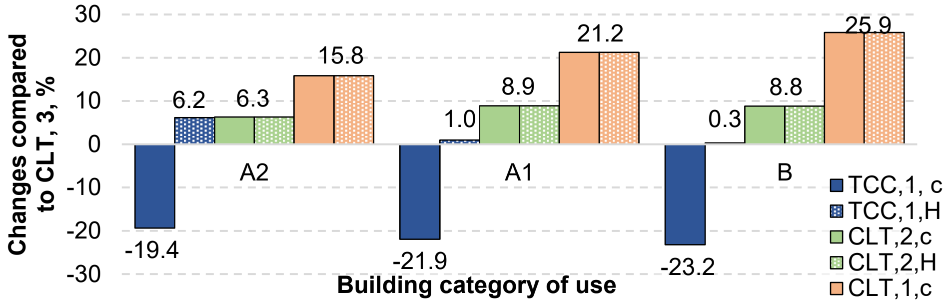

Figure 3: Changes in cost factor c and total height H values of CLT and CLT-concrete (TCC) slabs compared with CLT,3 slab characteristics. 1, 2 and 3 – vibration quality classes, respectively high, base and economic, A2, A1 and B – single house, multi-storey residential, office areas.

4. Conclusions

A comparison of CLT-concrete and CLT slab rationality for use as a floor structure for both residential and office buildings was made. The obtained results show the benefits of using TCC. A concrete layer with a rigid connection to the CLT slab significantly improves the structure's dynamic response. Using TCC reduces floor deflection while simultaneously reducing the overall thickness and cost of the structure.

Acknowledgement

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Quality assessment of timber frameworks joints by the non-model vibration analysis method

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1. Introduction

One of the essential parts of structural analysis and design is the calculation of joints. Joints play an essential role in the behaviour of the building structures. The joints can be classified as the rigid, semi-rigid and pinned dependently on its stiffness. The stiffness of the joints particularly influences the total structural firmness of buildings. The stiffness control of the joints during the building lifetime is essential to ensure that the current situation corresponds to the designed one and that the building is safe. The joint stiffness affects the distribution of internal forces in a structure both in members and joints (ultimate limit state) and deformations (serviceability limit state). The structural health of joints is directly related to their stiffness. Structural health monitoring (SHM) methods enable investigation and testing of structural joints behaviour during the whole service life of buildings. Choice of SHM method depends on the material of the joined structural members, its loading case, joints' structure and stiffness. Since the beginning of the 21st century, many SHM methods have been developed to investigate structural behaviour based on shock and vibration analysis. Vibration analysis methods allow determining possible damages of structural joints based on frequency response, modal shape and damping. Methods of vibration analysis are classified into two categories - methods using ready-made mathematical models and methods that do not employ such the models for vibration analysis (Boscato et al., 2019; Kamgar et al., 2012; Rahgozar, 2020; Fang et al., 2020; Masciotta et al., 2017). The present study aimed to propose a vibration analysis method for the quality assessment of structural joints based on the correlation of coaxial accelerations from sensors orientated coaxially in space. The method does not employ ready-made mathematical models for vibration analysis. A stand composed of timber beams with a moment joint of variable stiffness was developed and tested using the proposed method to verify the feasibility of the latter.

2. Materials and methods

A non-model vibration analysis method for correlating coaxial accelerations was developed. For the initial implementation of the hardware/software system, a method and measurement system implementing the principle of correlation of normalised coaxial accelerations measured in 3-D spwaswere proposed and experimentally tested. The developed measuring device consisted of an electrodynamic actuator, two 3-D accelerometers, a signals amplifier, an Arduino board for signals conversion and transfer, and a computer. The developed measuring setup and its major components are shown in Figure1 (Serdjuks et al., 2021). A non-model vibration analysis method was proposed and experimentally checked. The developed method is based on the mathematical analysis of structural joints' vibrations in 3 spatial directions using 3-D accelerometers located at different joint parts and orientated coaxially. A stand of timber beams was arranged as shown in Fig. 2 (Serdjuks et al., 2021) as a simple model in static loading and vibration test to verify the static diagram of the structure and evaluate the proposed method of coaxial correlations correspondingly. The stand consisted of a girder and an orthogonal beam forming T-connection and made of solid timber of C18 strength class with 150x50 mm cross-sections. The beam was freely supported, one with spans of 2.06 m and two spans of 1.5 m each. The girder and the beam were joined rigidly by steel corners and bolts.

(a) (b) (c)

Figure 1: (a) Developed measuring device; (b) electrodynamic actuator; (c) Arduino board.

(a) (b)

Figure 2: (a) scheme of the timber beams static loading; (b) accelerometers placement near considered joint with an indication of directions for vibration records fixations.

The vibration test examined the ability of the proposed method of coaxial accelerations correlation to determine the stiffness of the joint in the timber beam stand. The decrease of the rigid joint stiffness was modelled by the gradual removal of screws and bolts in the connecting steel corners (Serdjuks et al., 2021).

3. Results and discussions

Seven grades of stiffness were considered. Grade 1 (initial): rigid joint, all screws and bolts tightened. Grades 2-5: rigid joint with the decreased stiffness with gradually loosened screws and bolts. Grade 6 (Fig. 3(a)): pinned joint, with only one bolt. Grade 7 (Fig. 3(b)): absence of the joint between the girder and the beam.

(a) (b)

Figure 3: (a) Grade 6: pinned joint, with only one bolt; (b) grade 7: absence of the joint between the girder and the beam.

The beam was subjected to a vibration load provided by electrodynamics actuators, fixed on the edge of the beam, as shown in Fig. 2(a). Vibration response signals in both parts of the joint, the girder and the beam, were recorded in 3 spatial directions by two 3D accelerometers fixed respectfully on the girder and the beam (Fig. 2) and transferred to the computer. A vibration test was done at all seven grades of the joint. Differences in the vibration signals were noted in three directions: 0-1, 2-3 and 4-5. The highest values of peak values of correlation functions were obtained in the direction 4-5. The vibration experiment confirmed that the differences in vibration signals occur due to loss of the joint stiffness and the decrease of NPVCF values calculated from coaxial correlations reflect the grade of stiffness loss in the joint of the timber beams stand. It was shown that shear stiffness for 1-7 grades of the joint stiffness decreased consequently with the grade. The study showed that the differences between NPVSF parameters calculated based on 3D coaxial accelerometers correlation for the rigid, semi-rigid and pinned conditions of the joints enabled quantification and specification of the joint's shear and rotation stiffness. Analysis of vibration in 3D space enables assessment of the stiffness of joints of planar structures in general cases. For quality assessment of structural joints of spatial structures, the analysis of vibration in 6D space is preferable. It enables the evaluation of shear and rotation stiffness in 6 degrees of freedom (Serdjuks et al., 2021).

4. Conclusions

A vibration analysis method of 3D coaxial accelerometers correlation for quality assessment of structural joints in three spatial directions was proposed. The method is based on the mathematical analysis of natural vibrations of structural joints in 3D spatial directions using 3D accelerometers located at different parts of a joint and oriented coaxially. The method enables the evaluation of the changes of the structural joint's shear and rotation stiffness caused by the damaging or degradation of the joint during exploitation. The proposed method was experimentally tested on the timber T-joint in the rigid, semi-rigid and pinned conditions. It was shown that the difference between the peak values of the normalized correlation functions obtained for the rigid, semi-rigid and pinned joints enabled specification of the joints' shear and rotation stiffness.

Acknowledgement

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Flexible joints for timber structures under wind loading

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1. Introduction

Under the wind action, tall buildings are 3D bluff bodies that cause the flow to separate from the surface of the structure rather than follow the body contour. The asymmetric pressure distribution, created by flow recirculation around the cross section, results in an alternating transverse force as these vortices are shed. If the structure is flexible most wind-induced vibration is exhibited as lateral translation and rotation about the building vertical axis. Linear accelerations are primarily perceived by the vestibular system of the human body whilst angular accelerations are more detectable with visual cues (Rizzo et al., 2021). Two buildings with the same acceleration magnitudes and frequency content can lead to dissimilar performance if the duration of accelerations differs. Finally, the return period also determines the acceptable level of accelerations: a longer return period will naturally allow for higher accelerations to be tolerated.

Several studies have been executed to assess occupants' comfort (Rist & Svensson, 2016) but few studies systematically investigated the effects associated with wind-induced vibrations on non-structural elements, with a focus on specialized elements and smart building systems. The Eurocode has little information regarding comfort requirements for wind-induced accelerations (Eurocode 5). Other standards include some recommendations (Kwok et al., 2015).

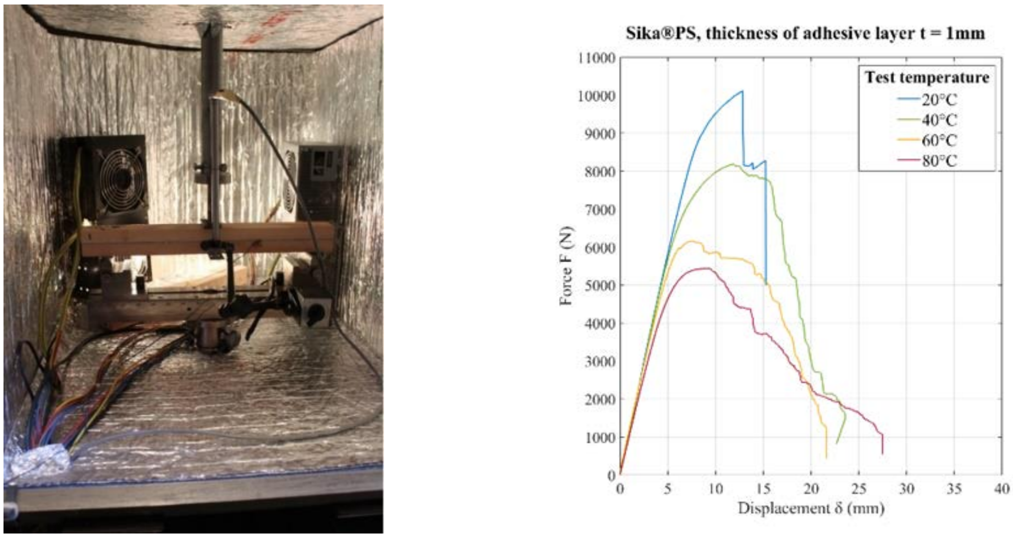
The current trend of increasing the height limits of timber buildings makes wind-induced vibrations a non-negligible issue. Lazzarini et al. (2021) discusses the dynamics of high-rise timber structures focusing on accelerations and comfort assessment of the currently tallest timber building in the world, namely, the 18-storey timber building in Norway. Flexible joints for structure and non-structural elements can mitigate the vibration effects on human safe and costs of repeating or maintaining.

A specific investigation focused on flexible joints for timber structures has been given by (Śliwa-Wieczorek et al., 2020a; 2020b; Śliwa-Wieczorek & Zając, 2021; Kwiecień et al., 2019; Pečnik et al., 2021) with the aim to estimate the force-displacements diagram depending on the temperature and the adhesive layer thickness as it is described in Section 2.

2. Mechanical experiments

The aim of the experimental program was to evaluate the influence of elevated temperature on both the load-bearing capacity of the laminated beams and the deflection. Additionally, the impact of adhesive layer thickness on the structural response of the joint was investigated for four temperature levels: 20°C, 40°C, 60°C and 80°C. In this experimental program, 6 timber beams were tested for each temperature and for each thickness (t = 1, 2 and 4 mm) with a three-point bending test (72 beams in total were tested).

Finite element model of the laminated beams was built and used to compare the measurements from the 3-point bending test. Fig. 1 illustrates the experimental setup and a typical force-displacements diagram for different temperatures.



(a) (b)

Figure 1: Experimental test on wood-adhesive-wood specimens: (a) setup and (b) results

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Human-Induced floor vibrations

Thomas Hillberger, University of Innsbruck (Austria)

1. Summary

Due to slender but also larger spans in timber constructions, the serviceability of slabs is becoming more and more important. Many contemporary developments have led to the need to pay more attention to areas such as vibration, despite adequate load-bearing capacity. This report aims to provide a summary of the state of the art with regard to person-induced floor vibration. In recent years, more research has been added to the range of walking person measurements. An important issue is the possible modelling. Different types of computational models in the literature are described and also compared in the following. Finally, active and passive options are presented, which are currently used to reduce annoying floor vibrations.

2. Introduction

Products such as cross laminated timber have contributed to the fact that large spans can currently be bridged and the load-bearing capacity no longer plays a role. The decisive factor for constructions in multi-storey residential buildings is often serviceability. Merely increasing the slab thickness to provide sufficient stiffness is no longer a viable option in the context of resource-conserving use of building materials. In relation to structures such as pedestrian bridges or in bridge construction in general, as in (Hamm, 2003) or (Zivanovic et al., 2005), person-induced vibrations have long played an important role. Also in structural engineering, more and more research work is invested in the measurements of human-induced excitation. Laboratory tests combined with field tests and computational models serve as the basis for predicting human-structure interaction (Chiniforush et al., 2019; Hassanieh et al., 2019). In order to properly assess the vibration behaviour of floor elements, models for calculation are necessary in addition to extensive measurements. Realistic models for dynamic effects caused by moving people are currently still a major challenge in the construction industry. Many models refer to the basic research of Bachmann & Baumann (1988). In the draft of the future Eurocode, the dynamic loads of persons are also increasingly addressed.

3. Human-Induced vibrations

The effects of person-induced vibrations have been studied in different materials. In the past, many experiments have been conducted with reinforced concrete elements or other materials, such as in (Hudson, 2013) or (Hudson & Reynolds, 2017). According to the most recent regulations, timber floors must be verified for serviceability limit state, which in case of induced vibration is related to the perception of annoying oscillations caused by walking. The live feel of timber floors is familiar to many, especially in single-family housing with a timber framework. However, this problem is not limited to timber-framed residential buildings: the trends of seeking large open-spaced architectural layouts and adopting new construction practices certainly affect timber floors' serviceability significantly. The ability to predict timber flooring systems' behaviour remains a difficult task and a topical subject. The assessment of timber buildings' vibration performances under walk-induced vibrations and the comfort requirements for users have been investigated by many researchers for many years (Smith et al., 2007; Ohlsson, 1982; Smith & Chui, 1988; Hu et al., 2001; Hamm et al., 2010). This effort has been translated in more recent in standard rules proposal for the new generation of Eurocodes (Hamm et al., 2020). However, the expansion of timber construction also in application where steel or concrete was dominant, could also bring to the need to apply also to timber floors more advance verification approaches that have been proposed for traditional material. The effect of support conditions or vertical partitions should be also taken into account. The vibration behaviour is of course also significantly influenced by the support conditions. For example, in (Huang et al., 2020), the effects of person-induced vibrations on different types of support of CLT elements are investigated. Simulations with the software OPENSEES were compared with laboratory tests.

4. Load consideration for slab structures

An important issue in calculating the effects of person-induced loads is certainly the load models used in the calculation. An overview regarding some models used until 2018 is provided by Muhammad et al. (2019). It is also noted in this research important key parameters of the models for walking individuals. An essential point here is also models for multiple pedestrians. However, a lot of work has also been done in this regard in the last much years. In (Muhammad & Reynolds, 2020), for example, the consideration of different test subjects and thus different types of loading is addressed. Compared to the deterministic approaches based on Fourier series, the probabilistic model of this work is intended to account more realistically for real walking in terms of temporal and spatial characteristics. An important point is certainly the overlapping of the individual steps. In the research work of Cai et al. (2019), these overlaps between successive steps are analysed in a series of finite element simulations and their effects on three different floor plates are determined. That the evaluation of the serviceability of floors currently occurs from a single person's model is addressed in (Mohammed & Pavic, 2019). The authors also address the difficulty of realistically modelling the movement behaviour of multiple people. In this paper, they therefore refer to the social forces model in their simulations to simulate the motion behaviour of multiple people.

5. Passive and active damped slab structures

The use of passive and active systems to reduce problematic vibrations are not inventions of the present. These systems have been used in bridge structures, for example, for decades. This sector is also becoming increasingly important for building construction. Systems such as tuned mass dampers are being investigated, for example, in the research work of Chen et al. (2019). However, the active systems also need to be mentioned in the countermeasures regarding undesirable person-induced swinging. Passive vibration dampers in bridge structures are not uncommon. In building construction, more research is also being done in this area. For example, in (Huang et al., 2021), a rotating inertia damper with double tuning is proposed, which introduces an inert-based cubic control system to better match human-induced floor vibrations. However, adaptive passive systems are also used in some cases. For example, an adaptive passive multiple TMD system with variable mass is investigated in (Wang et al., 2020). The results of this research show that the system can return itself independently, providing the best vibration control. Active solutions have been less investigated for timber floor structures at present. In general, the existing literature is mainly based on other materials. This means that timber construction certainly has potential upside in this area. As in works by Díaz & Reynolds (2010) or Wang et al. (2018), special control laws of active countermeasures of person-induced vibrations in floors and bridge structures are addressed.

Effects of the support conditions on timber floor vibrations

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1. Introduction

Serviceability issues of timber floors are commonly related to vibrations, especially for longer span floors. Conventional approaches for ensuring adequate vibration serviceability involve limiting responses of the floors, such as static load deflections, natural frequencies and impulse response magnitudes, or combinations of those (Toratti et al., 2018). It is widely accepted that the supports play an important role in the vibrational response of the floors, but there exists no clear guidance for design. Typically, the supports on the edges of timber floors are assumed as either ideally pinned or free. For example, Eurocode 5 does not give guidance for any other scenario. However, many existing studies indicate that the assumption of a pinned connection is not always valid, and the supports can exhibit significant vertical flexibility and/or rotational stiffness. Both affect the static and dynamic responses of the floor, leading to different results when compared to the theoretical predictions. These two non-ideal conditions are shortly reviewed and discussed.

2. Vertical flexibility of the supports

Vertical support flexibility decreases the overall stiffness of the floor, leading to lower natural frequencies and higher static deflections. There are many causes for vertical flexibility, such as (i) vibration isolation layers, (ii) floor supported by mechanical connectors, (iii) flexibility of supporting structural members (e.g., beams, walls, or columns) and (iv) incomplete contact interfaces. Use of vibration isolation layers, placed between the floor and the supports, is a common method to mitigate sound transmission problems in timber buildings (see Figure 4 (a)). The behaviour of timber floors supported with and without vibration isolation interlayers were compared in Jarnerö et al. (2012), Bolmsvik & Brandt (2013) and Basaglia (2019). The main trend is that vibrational isolation interlayers tend to decrease the natural frequencies and increase damping ratios of the floors. However, the effects can be even opposite for some vibration modes and test setups had large variety, so no complete conclusions can be drawn from these studies. Bolmsvik & Brandt (2013) mention that the mean acceleration levels of the floor increased significantly below 40 Hz frequencies, when interlayers were used. Besides that, also the use of mechanical connectors to support the floor (Figure 4(b)) can affect the vibrational behaviour (e.g., Chui et al., 2004).

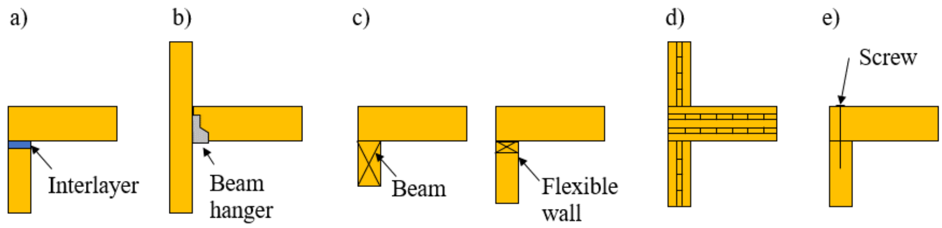

Figure 6: Examples of timber floor edge details inducing vertical flexibility (a, b, c) and rotational restraints (d, e).

Vertical flexibility can also result from the flexibility of the supporting member (Fig. 1 (c)) or incomplete contact interfaces. The effect of supporting beams has been already well recognized and is included in the current draft of Eurocode 5 revision. The effects of other types of components, however, are typically neglected. The authors' own investigations on two-way timber-concrete composite plates (Jaaranen & Fink, 2022) indicated pronounced effects from the support flexibility when the plate was supported on a light timber wall. A conclusion from simulation studies was that for accurate results, the support flexibility needs to be accounted for. Furthermore, in two-way timber floor systems, uplift in the corners can lead to imperfect contact conditions, unless the floor edges are tightly fixed to the supports. The response with imperfectly supported edges is different compared to predictions assuming ideal pinned supports on edges.

3. Rotational restraints

Rotational restraint effect increases the overall stiffness of the floor, leading to higher natural frequencies and lower static deflections. These restraints can be due to (i) floor being installed between walls or (ii) floor edges being screwed tightly to the supports. In CLT construction, a common solution is to place the floor panels between the adjacent walls as shown in Fig. 1(d). This introduces rotational stiffness to the joint due to clamping effect. Literature review by Zhang et al. (2019) indicate large differences in the CLT floor stiffness due to rotational restraints caused by different support conditions. According to simulation studies in (Akter et al., 2021), the main factors influencing the stiffness are thickness of the walls and the vertical load in the wall, although other factors, such as floor plate thickness, also have effects. The clamping effect can be also introduced by screwing down the floor plate to the supports (Fig. 1(e)). A variety of test results for CLT plates, clamped to the supports by screws or external force, can be found in Hernández Maldonado (2021). The general trend is that clamping increases stiffness, therefore increasing fundamental natural frequencies, and decreasing static deflection, while damping ratios were independent of the rotational stiffness. The effects and analysis of rotational restraints has been discussed more in general by e.g., Malo & Köhler (2013) and Zhang et al. (2019), with related case studies.

4. Conclusions

Support conditions have a clear impact in the vibration behaviour of timber floors, and assuming conventional pinned supports may lead to significant inaccuracies in the predictions. Vertical flexibility decreases stiffness of the floors and designs may be unconservative. For vibration isolation layers, it is not always clear whether the overall effects are adverse or beneficial for vibration performance, and more investigations may be needed. For other causes of vertical flexibility, the research could be directed for improving and validating analysis methods as well as identifying conditions, in which these effects need to be accounted for. Rotational restraints lead to improved performance compared to pinned assumption. Therefore, there may be a large potential for material savings, if the effect can be accounted for. To avoid under-performance, the rotational restraint effects could be validated under in-situ conditions.

Modelling timber building elements by Finite Element Analysis

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1. Introduction

Timber buildings are prone to annoying vibrations and low-frequency impact sound. Moreover, the design in terms of serviceability is generally largely influenced by its vibration performance (Dolan et al., 1999). Hence, improvement of floor performance and, consequently, reliable prediction tools are necessary. Often, timber floor vibration characteristics are evaluated by empirical criteria or simple formulas using only the fundamental frequency or other measures in combination with it. Nevertheless, it has been shown that higher order modes should be included (Alvis et al., 2001). Therefore, numerical methods, e.g., the finite element (FE) method, offer a good alternative but require to be tuned to fit the experimental data. The following report gives a short overview of recent advances in FE modelling of timber floors and buildings and its difficulties.

2. Model Updating

Experiments validate the applicability of a chosen model; however, usually, models do not represent the experimental results accurately at the first guess. Therefore, model updating is performed to match measurements and simulations well. In the process of model updating, parameters of significant variability are tuned by an iterative procedure to optimize an error function that represents the problem at hand best (Mottershead et al., 2020). Generally, for vibration analysis, accurate stiffness- and mass-related parameters are required, which are tuned by means of eigenfrequencies and mode shapes. Basaglia et al. (2020) used the natural frequency error for the eigenfrequencies and the modal assurance criterion (MAC) to compare the mode shapes, which are common measures. By means of this, a sufficient match of numerical and experimental data is often possible for the first couple of modes, e.g., less than 6 % for the natural frequency error and a MAC-value above 0.73 in (Basaglia et al., 2020). However, if damping comes into play, the model updating becomes more complex since frequency response functions (FRFs) are utilized. FRFs are computationally more expensive to calculate, and many different damping models exist, making it harder to identify an appropriate setting. When using FRFs, criteria such as the Cross Signature Assurance Criterion (CSAC) or the Cross Signature Scale Factor (CSF) are used as a measure for comparison (Marinone et al., 2014). Nevertheless, an accurate match is often difficult to achieve in terms of FRFs (see, e.g., (Qian et al, 2019)). For an accurate prediction tool of vibration levels and sound insulation properties, not only eigenfrequencies and mode shapes are necessary, but also vibration amplitudes, which depend on damping. Mostly, measured damping values or parameters given in standards are taken as an easy alternative to damping-related model updating (see, e.g., (Basaglia et al., 2020)). However, further improvement of the prediction tools can be achieved by fine-tuning damping properties in the used FE models.

3. Stochastic Investigations

Furthermore, variations of input parameters for the models give deeper insight and provide a safety margin for the numerical results. To this aim, often Monte-Carlo simulations are performed (see, e.g., (Persson et al., 2019)). Furthermore, generalized polynomial chaos expansion can be used to calculate the stochastic vibration response (Sepahvand et al., 2012) or, additionally, identify uncertain material properties (Sepahvand et al., 2014). Probability distributions are then considered for the inputs, and samples are drawn to compute the response in terms of statistical properties such as confidence intervals. Moreover, to analyse which parameter's uncertainty might lead to strong variations in the response, sensitivity analyses are conducted. In (Basaglia et al., 2020), high sensitivity coefficients have been identified for some of the material properties as well as the support conditions. Furthermore, joints have a great influence on vibroacoustic behaviour (see, e.g., (Chocholaty et al., 2022)).

3.1. Material Properties

Material properties have a large influence on the resulting vibrations. The in-plane moduli of elasticity, density, and Poisson ratios reveal large sensitivity coefficients with respect to the eigenfrequency of the structures. On the other hand, the modulus of elasticity through the thickness of a, e.g., plate, as well as shear moduli G_{xz} and G_{yz}, are assumed to have negligible influence (Basaglia et al., 2020). Furthermore, the material parameters of wood show substantial variation due to its natural characteristic leading to, e.g., growth irregularities or knots (Persson et al., 2019). Consequently, it is essential to consider the variability in wooden material properties in FE analyses.

3.2. Supports

As boundary conditions strongly influence the modal behaviour and the modal behaviour has significant effects on the low-frequency response of structures, the supports of a building element also are an important part of a model. Basaglia et al. (2020) support this by computing high sensitivity coefficients of the observed modes w.r.t. support stiffness, especially in the vertical direction. Additionally, (Pasca et al., 2021) show that although free boundaries are the easiest to simulate, they might be hard to achieve in experimental settings. They further conclude that components at test are susceptible to their supports making it more difficult to find an accurate model.

3.3. Joints

Joints also significantly influence the vibrations and acoustics of a structure. As Persson et al. (2019) point out, variability due to different types of fasteners, as well as variability between nominally identical joints, occur. Moreover, modelling techniques vary strongly and also influence the numerical results. Furthermore, the effects, e.g., friction, within a joint might differ depending on the loading, which indicates nonlinearity. A comprehensive study on the influence of joints of a timber-steel structure, the inherent nonlinearities, and the variation among different fasteners has been studied by Chocholaty et al. (2022). Hence, uncertainties due to the model itself as well as the input parameters, i.e., material properties, supports, and joints, are an essential factor in capturing the behaviour observed by measurements. Persson et al. (2019) found a 4 dB difference for a 90 % confidence interval for the vibration dose value; hence, the inclusion of uncertainties in a prediction tool could make a difference in a design engineer's decision.

4. Application to taller timber buildings

Generally, the dynamic properties of a tall timber building are not known beforehand, which is why the fundamental frequency is often vastly underestimated. Currently, modal properties of buildings are identified on-site by means of ambient vibration testing or, as recently done, by input-output modal testing (Kurent et al., 2021). However, testing tall buildings is costly and complex. Therefore, modelling approaches could offer a good supplement during construction or even a handy tool in the design process. Consequently, further research in modelling taller timber buildings and on single timber building elements could benefit the overall design process.

5. Conclusions

As explained before, the design process of taller timber buildings can take advantage of elaborate modelling approaches. Those models can be built upon accurate models of single timber components. In this context, the uncertainty of materials, supports and joints are essential parameters that might improve the design and performance of timber buildings in acoustic as well as vibrational sense. Since experimental studies validate the models, model updating processes also amount to an important part. Hence, future studies can deal with the inclusion of models in the design process of taller timber buildings considering all available data.

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Design of taller timber buildings subjected to accidental loads: a state-of-the-art review

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Cost Action CA20139

Holistic design of taller timber buildings - HELEN

Working Group (WG) 3

Accidental Load Situations

State-of-the-art (STAR) report

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Forward

This report is a publication of the European Network **COST Action CA20139** “Holistic design of taller timber buildings – **HELEN**”, established with the aim to “*work towards optimized holistic approaches to improve the performance of taller timber buildings and to widen their competitiveness and use across the EU and rest of the world*” (https://cahelen.eu/).

The activities conducted in the first year of the Action by the **Working Group (WG) 3** - Accidental load situations - are summarized in this document in the form of a state-of-the-art report (**STAR**) regarding design, analysis and construction methods of taller timber buildings subjected to load situations due to **earthquake**, **fire** and **blast**.

The report is the result of a deep review of scientific literature, international projects, national regulations, design guidelines, as well as case studies. Particular attention has been paid to the potential interactions with other fields of design and to the efforts made in the recent years to overcome the limitations for the progress in the construction market of timber buildings under seismic, fire and blast loads.

The information collected in this STAR document represent the starting point of discussion to identify solutions, research targets, methods and resources for the future of taller timber buildings under seismic, fire and blast loads following a holistic design approach.

Three different sub-groups (SGs) have been defined for WG3 STAR activities, namely **SG1 - Seismic Loads**, **SG2 - Fire** and **SG3 - Blast**. For each SG, different subtopics have been analysed and discussed.

This report is structured into three parts. **Part 1** includes the review conducted by SG1 on the seismic design and seismic analysis of taller timber buildings and consist of seven documents. The review regarding the fire design situations is summarized in **Part 2** through four documents. **Part 3**, composed of four documents, addresses the review of current knowledge on blast design of timber buildings.

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Part 1

Seismic Loads

Sub Group (SG) 1

WG3.SG1.01

Lateral Load Resisting Systems

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1. Introduction

The structural behaviour of Tall Timber Buildings (TTBs) subjected to earthquake actions is governed to a large extent by the Lateral Load Resisting Systems (LLRSs), whose performances are mainly dependent on their geometry, the Engineering Wood Products (EWPs) adopted for different structural elements, and the type of connections used.

An overview of most adopted systems is presented, and associated examples of constructed buildings are introduced.

2. Shear wall system

Shear wall systems used as LLRS for TTBs are mainly composed of Cross-Laminated Timber (CLT) panels. The benefits of such systems are reasonably high in- and out-of-plane stiffness and strength, rapid construction process, and established design provisions (A. Ceccotti & M. Follesa, 2006). Alternatives to CLT are Glued Laminated Timber (Glulam), Laminated-Veneer Lumber (LVL), Laminated-Strand Lumber (LSL), and special mass plywood panels.

In general, there are two types of shear wall constructions, see Figure 1:

- Platform system, in which the floors at each storey are the base of the shear wall for the next level. Hence, each floor is the interval between the shear walls of adjacent storeys.
- Balloon system, in which the shear wall is erected continuously over multiple floor intervals.

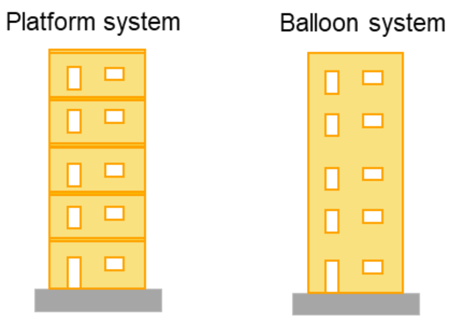

Figure 1: Shearwall construction types: Platform (left) and Balloon (right) system.

Platform system is known as a more dissipative system since more connections are involved, leading to higher redundancy. Capacity-based Design (CD) is incorporated into design of such system in high seismic regions by providing dissipation through relatively ductile connections and over-protecting non-dissipative elements to avoid brittle failure (Casagrande et al., 2019).

Many examples of low-to mid-rise buildings composed of CLT shear walls are built worldwide, such as:

- Bridport house in London, UK (2010); up to eight storeys made of platform-type CLT shear wall.

- Origine in Quebec City, Canada (2017); thirteen storeys made of balloon-type CLT shear wall.

3. Timber frame system

LLRS in timber frame systems may be provided by braces or moment resisting connections, as can be seen in Figure 2a. The ductile mechanism in the connections at the end of the diagonal braces dissipate energy while other members and connections remain elastic (Chen & Popovski, 2020). The connections used in braces may be considered relatively ductile if they are properly designed, such as bolted connections without risk of wood splitting.

Moment resisting connections were rarely used as LLRS due to the difficulty in details. Ductile connections are needed to provide enough energy dissipation while minimizing shrinkage. Some examples of such connections are bolts with tight-fit pins, glued connections, etc.

Examples of timber frames used as LLRS in mass timber constructions are:

- Mjøstårnet in Brumunddal, Norway, (2019); eighteen storeys composed of braces as LLRS.
- UBC Okanagan Fitness and Wellness Centre in Kelowna, Canada (2013); tapered moment-resisting connections were utilized.

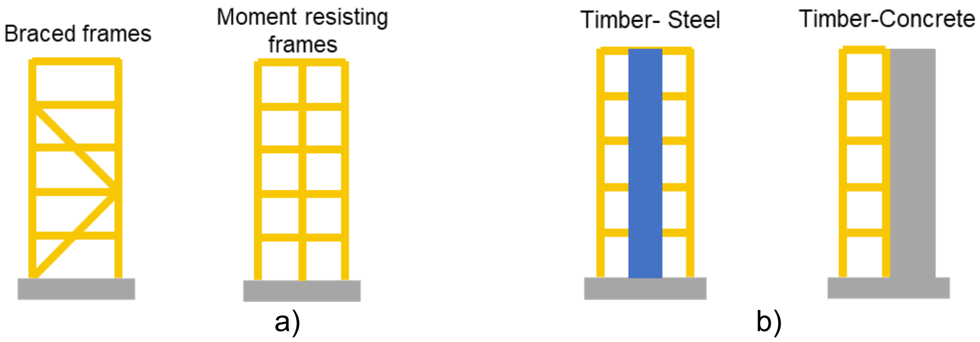

Figure 2: Timber frame LLRSs: brace (left) and moment-resisting (right) frame, (a); Hybrid LLRSs: timber-steel (left) and timber-concrete (right) systems, (b).

4. Hybrid systems

Hybrid systems represent those LLRS, in which timber elements are combined with steel and/or concrete elements (Figure 2b). A large variety of hybrid systems can be adopted as LLRS, however, one of the most adopted solutions consist of a reinforced concrete core that fulfils the structural performance and simultaneously is the stair and lift shaft, as is the case with conventional reinforced concrete high-rise buildings. Such a system presents several advantages such as: (i) it eases the limitation related to fire safety of TTBs as stairs and lift shafts are constructed of non-combustible materials, (ii) its performance under seismic actions is significantly less complex to be designed for the majority of practitioners, (iii) it represents a cost-optimized solution compared to other timber alternatives.

Examples of LLRS hybrid systems for TTB are:

- Haut project in Amsterdam, which is one of the tallest timber hybrid buildings with a 73m height (https://www.arup.com/projects/haut).
- Brock Commons Tallwood House, residence building, Vancouver (Canada).
- MEC head office composed of steel-braced LLRS, Vancouver (Canada).

WG3.SG1.02

High-performance connections

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1. Introduction

The primary role of high-performance connections for Tall Timber Buildings (TTB) is transferring forces and accommodate displacements between structural elements. They assure proper stiffness of timber structures, as well as dynamic behaviour features such as ductility and energy dissipation capacity of buildings in seismic areas. In timber structures subjected to seismic events, the exposure of structural connectors to cyclic loads is one of the dominant issues of stiffness loss and irreversible damages. Therefore, the choice of a proper connection system is generally made by considering not only the strength, but also other mechanical properties such as the stiffness, the ductility and the capacity of dissipating energy, which are all properties influencing the response of TTBs during a seismic event. The properties, geometry and mechanical behaviour of connections for TTBs are primarily related to Lateral Load Resisting System (LLRS), in which they are intended to be used. Considering the main LLRSs adopted for TTBs shown in Figure 1, two main connection categories can be identified: (i) connections for panel elements, and (ii) connections for linear elements. The former serves to connect timber panels to the storeys below and/or to the foundation and to transfer the horizontal and vertical forces due to the seismic actions, see Figure 2 (left). The latter serves to transfer the bending moments and the internal axial and shear forces due to the seismic actions, see Figure 2 (right).

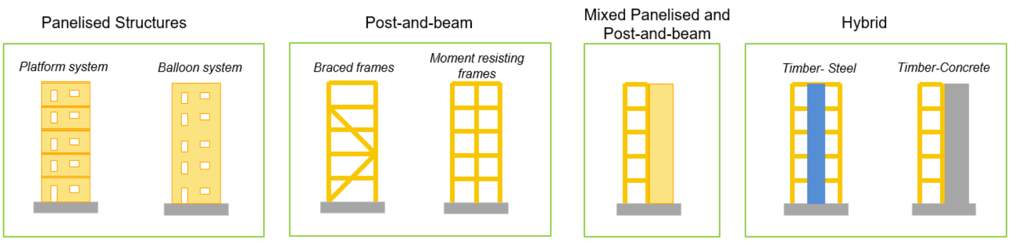

Figure 3: Different LLRS for TTBs.

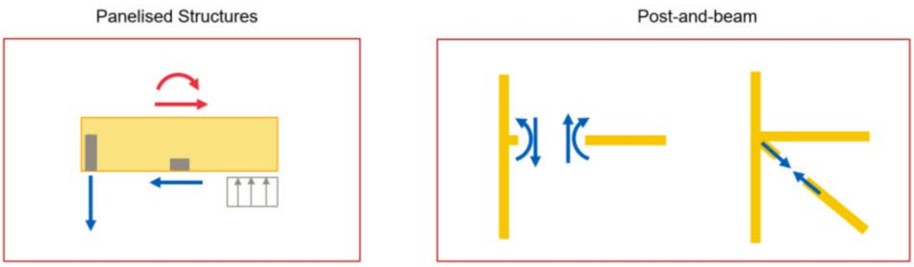

Figure 4: Internal forces in connections of different LLRS for TTB.

Due to their crucial role in seismic performance of timber buildings, connections in timber structures have been the subject of extensive research and development over the last decades and have undergone technological progress that has led to an increase in their mechanical performance and enabled the construction of modern TTBs. In the next sections, an overview of traditional and innovative high-performance connections is presented.

2. Traditional connections

Traditional connections of timber structures in seismic areas were primarily made of carpentry type joints, whereas nowadays they are generally metal dowel-type connections with fasteners such as nails, bolts, dowels, screws or specially formed metal connectors such as toothed-plates, ring and shear plates, metal brackets of various shapes like hold-downs and angle brackets (Porteous & Kermani, 2007)). Stiff and high strength adhesive type connectors joining structural elements such as composite beams with timber-to-timber or timber-to-concrete joints and glued-in steel rods (Borgström, 2016) are used primarily for non-dissipative connections. Traditional metal type connections adopted in low-rise cross-laminated timber (CLT) structures were inherited from light-frame timber (LFT) structures and include metal brackets and dowelled slotted-in steel plates of various geometries used to undertake vertical-tensile and horizontal-shear forces, and self-tapping partially threaded screws used to transfer shear forces (Tomasi and Sartori, 2013, Gavric et al., 2015, Izzi et al., 2018)). These types of connections were proven adequate for low-rise CLT buildings when accepting a certain degree of damage in the joints and residual deformation in the timber assemblies. When structural designers try to adopt traditional connection systems in TTB, they might encounter difficulties that reveal some relevant issues such as insufficient strength and stiffness capacity, and possible brittle failure modes with the lack of energy dissipation. To overcome these limitations, development of innovative high-performance connections is crucial.

3. Innovative connections

To overcome common drawbacks of traditional connections for timber buildings in seismic areas, such as stress concentration and incompatibilities under large deformations (Moroder, 2016), insufficient cyclic resistance, ductility and energy dissipation capacity, different typologies of innovative high-performance connections have been developed in the last years. Several innovative solutions are available, such as tube connections (Schneider et al., 2018), X-Rad (Polastri et al., 2017)), Spider (Maurer et al., 2021), bi-directional behaviour metal plate connections (D'Arenzo et al., 2021), hyper-elastic hold downs (Asgari et al., 2021), pinching-free connectors (Chan et al., 2021), U-shaped flexural plates (Chen et al., 2020), polyurethane thick flexible shear and glued-in steel rod joints (Pečnik et al., 2021, Azinović et al., 2018), which are durable under fatigue tests (Kwiecień et al., 2019). Most of the abovementioned innovative connections represent solutions adopted to improve the structural behaviour of traditional connections, ensuring higher strength, stiffness, dissipation capacity and overcoming issues related to brittle failure mechanisms. On the other hand, some of the presented innovative connections differ substantially from traditional connections and their adoption in some cases results in a different seismic behaviour of structural timber systems.

4. Energy dissipation connections

Various ideas improving energy dissipation properties of connections were also investigated and proposed in the recent years. Slip-friction devices, consisting of a steel plate encased in the timber element and two built-in abrasive-resistant side steel plates held together with bolts and disc springs, were proposed as a hold-down for mass timber shear walls (Loo et al., 2014). High dissipation energy capability can be attained in the system without pinching, displaying the desired flag-shaped hysteretic behaviour. Slip-friction connectors were further advanced into resilient slip friction (RSF) connectors, which provide a damage-free self-centring solution for CLT shear walls (Hashemi et al., 2018). The self-centring capacity is enabled by the zigzag-like connection interface between the cap and slotted plates. High-force-to-volume damping devices (HF2VDDs) made of a steel shaft sliding within a tube (Vishnupriya et al., 2018) were also proposed. The damping and energy dissipation are provided by an extruded lead mounted around the shaft. Dickof et al. (2021) proposed Internal Perforated Steel Plates as end-brace connections in timber frames and as base shear connectors in CLT shear walls to avoid the common dowel yielding and wood crushing failure mechanisms.

WG3.SG1.03

Seismic Protection Technologies

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1. Low damage and self-centring systems

The low-damage systems and self-centring concepts are based on automatic mechanisms for returning the main irreplaceable parts of structural systems to their initial positions after earthquakes. Therefore, several innovative systems and models have been proposed to increase the self-centring capacity of Taller Timber buildings (TTBs). Table 1 summarizes low-damage and self-centring systems.

Table 1: Low-damage and self-centring timber systems literature review

System type	Author	Year
Resilient Slip Friction Joint (RSFJ)	Zarnani & Quenneville	2015
Self-Centring Rocking timber Wall system (SC-RW)	Hashemi et al.	2016
Hybrid steel-timber wall system using the RSFJs	Hashemi et al.	2017
RSFJ as hold-downs in rocking CLT walls	Hashemi et al.	2018
Self-Centring Steel-Timber Hybrid Shear Wall (SC-STHSW)	Cui et al.	2020
Self-Centring Timber Brace (SC-TB)	Yousef-Beik et al.	2020
Elliptically profiled CLT walls	Ricco et al.	2021
Rocking CLT walls with the Uplift Friction Dampers (UFD)	Tatar & Dowden	2022

Zarnani and Quenneville (2015) proposed a damage-free connection which is called Resilient Slip Friction Joint (RSFJ). The RSFJ has two middle and two cap serrated plates which are compressed by a bolt and disc spring system. The RSFJ has been used by Hashemi et al. (2017) in hybrid damage avoidant steel-timber wall systems to prevent residual displacement and minimize damage. Hashemi et al. (2018) utilized RSFJ as hold-downs in rocking CLT walls to reduce the residual displacement and improve the self-centring capacity of the rocking CLT walls. An Uplift Friction Damper (UFD) composed of tension bolts and disc springs combined with an angled abrasive friction interface has been used as a low-damage and energy dissipater connector in rocking shear walls (Tatar and Dowden 2022). In the proposed UFD, post-tensioned (PT) rods provide the self-centring response while two angled steel wedges slide on each other to dissipate energy. Ricco et al. (2021) proposed using elliptically profiled CLT walls to form a rocking story in multi-story CLT buildings. The system is a rocking soft story based on the elliptical rolling rod isolation. Using soft story as seismic isolator buffers the upper stiff part of the building from ground motions during earthquakes.

2. Post-tensioned systems

Post-tensioned timber technology can provide increased strength and stiffness for mass timber seismic load resisting systems while also providing energy dissipation and re-centring capabilities. The state-of-the-art research and implementation of the post-tensioned timber systems was reported by Granello et al. (2020) and some key research is listed in Table 2. The research shows that the controlled rocking mechanisms of elastic post-tensioning provide self-centring action to eliminate residual drifts, while additional dissipative devices, such as replaceable steel fuses, increase the damping and reduce lateral displacements of multi-storey buildings. The research on the stiffness of connections is still limited, health monitoring and maintenance also require further investigations. Furthermore, the interaction between structural and non-structural elements under seismic loading requires further considerations to achieve a holistic design (Brown et al. 2022).

Table 2: Post-tensioned timber systems literature review

System type	Relevant research
Post-tensioned timber shear walls	1. Laminated veneer lumber (LVL) walls (Palermo *et al.* 2005) 2. CLT walls (Pei *et al.* 2019, Brown *et al.* 2022) 3. Single and coupled Post-Tensioned CLT (PT-CLT) walls (Akbas et al. 2017) 4. Post-Tensioned CLT Shear Walls with Energy Dissipators (Chen et al. 2020)
Post-tensioned timber frames	1. Beam-column connections (Iqbal, Pampanin, and Buchanan 2016, Li, He, and Wang 2018) 2. Frames (Newcombe, Pampanin, and Buchanan 2010, Di Cesare et al. 2020) 3. Post-tensioned glulam frame (Ding et al. 2021)

3. Supplemental damping systems

Seismic protection through supplemental damping aims at decreasing the structural demands and consequently decreasing inter-story drifts while potentially adding stiffness in the structural systems by increasing inherent damping dissipation through the addition of supplemental devices called dampers. These devices can increase the equivalent viscous damping and are activated by: (i) displacement (e.g. metallic dampers, hysteretic devices, friction dampers); (ii) velocity (e.g. viscoelastic dampers), or (iii) motion (e.g. tuned mass dampers). The summary of state-of-the-art research is summarized in Table 3. Applications in-between gravitational and lateral force resisting systems of mid- to high-rise timber buildings may be increasingly exploited in the future, which also applies to rocking systems, yet so far most of research has been performed for low- and mid-rise structural systems. Clear definitions for the calculation of overstrength for timber assemblies, as well as detailing of connections to the gravity system is greatly needed in codes.

Table 3: Supplemental damping systems literature review

System type	Relevant research
Metallic dampers and Friction dampers Viscoelastic and fluid viscous dampers Tuned mass dampers	1. Seismic protection technologies for timber structures (Ugalde et al. 2019) 2. Damping in Wood-Frame Shear Wall Structures (Jayamon et al. 2018) 3. Base Isolation and Supplemental Damping Systems for Seismic Protection of Wood Structures (Symans et al. 2002)

4. Passive control systems

With the new challenge for designers to accommodate the high load demand and ductility, innovative dissipating devices have been combined with mass timber structures as passive control systems as listed in Table 4. The passive control system can minimise damages to timber elements when providing enough structural performance by using capacity design principles. Residual deformation of structures with passive control systems is an issue for the reuse of structures after a major earthquake. Unlike those passive control systems for steel structures, many mass timber structures with passive control systems are not in current standards. Design information is missing such as force reduction factors and ductility factors.

Table 4: Passive control systems literature review

System type	Relevant research
Timber frame with buckling restrained braces (BRBs)	1. Timber casing BRBs (Murphy, Blomgren, and Rammer 2019, Takeuchi *et al.* 2022) 2. Frame with BRBs (Dong *et al.* 2020)
Mass timber with perforated steel fuses	1. Shear wall application (Blomgren et al. 2018) 2. Brace application (Daneshvar et al. 2022)

Mass timber with Resilient Slip Friction Joint (RSFJ) connections	1. Hold-downs for shear walls (Hashemi, Zarnani, and Quenneville 2020) 2. Braces for frames (Yousef-beik *et al.* 2021)

WG3.SG1.04

Design strategies and seismic analysis

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1. Introduction and background

The seismic design process of taller timber buildings typically involves two main aspects: "design strategies" and "seismic analyses". The former deals with the design methodology used to achieve adequate performance levels for different limits states. The latter aims to evaluate the seismic demand on buildings and structural members.

2. Design strategies

2.1. Performance Based seismic design & limit states

The seismic performance-based design (PBD) (Naeim, 2010, Ghobarah, 2001) allows a control of the structure's vulnerability and economic losses during the structure's lifetime for different earthquake levels which, are related to the limit states defined through specific demand parameters (e.g. inter-storey drift, storey acceleration or the deformation of the structural elements). Design codes follow the PBD applying the Force-Based method by performing the strength capacity verifications for the ultimate limit states, whereas the serviceability limit states are verified by limiting inter-storey drifts. However, the values of inter-storey drift limits reported in design codes seem to be more appropriate for low- to mid-rise timber buildings rather than taller buildings since the deformation contribution due to the rigid body displacement may be significant at the upper levels (Willford et al., 2008).

2.2. Force vs Displacement Based-Design

The performance and the limit states could be achieved by following different design methodologies such as Force-Based Design (FBD) or Displacement-Based Design (DBD) methods (Loss et al., 2018). FBD is widely used by applying equivalent lateral force (ELF) method or with the modal response spectrum (MRS) method (Follesa et al., 2013, Seim et al., 2014). DBD is mainly used in research (Rinaldin et al., 2017, Sustersic et al., 2016). However, the application of DBD methods for timber building is in an early stage (mainly for Direct-DBD and Modal-DBD) and future investigations are needed for taller and hybrid buildings (Loss et al., 2018).

2.3. Capacity design

The capacity design is a seismic design approach used to promote a dissipative behaviour of a structure. The method consists of designing brittle mechanisms stronger than the ductile mechanisms to achieve a ductile failure. Since timber elements are characterized by brittle behaviour, the energy dissipative behaviour is concentrated in mechanical connections. The connections should ensure adequate ductility and low-cycle fatigue strength (Casagrande et al., 2020). The capacity design procedures should be satisfied at the local (connections, timber elements) (Ottenhaus et al., 2021) and global (entire building) level too. Several studies focused on the capacity design approach of mechanical connections (Jorissen & Fragiacomo, 2011, Schick et al., 2013, Vogt et al., 2014, whereas Casagrande et al., 2019 investigated the capacity design at the global level on multi-storey timber buildings (CLT and LFT). However, no specific rules are available for taller timber buildings. Codes do not define how to apply the methodology and which are the dissipative/brittle mechanisms for low-rise buildings (Chen & Chui, 2017).

3. Seismic analysis

3.1. Dynamic properties & Fundamental Period

In seismic design, the dynamic properties (natural frequency, mode shape, damping and linear/non-linear behaviour) allow a correct prediction of the seismic demand and the dynamic response. A numerical comparison between CLT and light-frame structural types (Edskär & Lidelöw, 2019) shows that both systems provided similar natural frequencies due to a balance of stiffness and mass (CLT have higher mass and stiffness than the frame system).

3.2. Seismic and wind loads

Due to the flexibility of taller timber buildings (Foster & Reynolds, 2018), the main design action of the lateral-resisting system could be wind load instead of seismic load as shown in several researches (Tesfamariam, 2022, Shaligram & Parikh, 2018, Chen & Chui, 2017, Tesfamariam et al., 2019). The design action is a function of the dynamic and geometric properties of the whole building and the seismic hazard site. The seismic action is calculated by estimating the design acceleration (accounting for the dissipative behaviour) and the total mass. Theoretically,the seismic action could be limited by reducing the seismic mass and increasing the dissipative and damping capacities. In practice, the possibilities for influencing seismic loads are unfortunately usually limited. The mass is determined by different structural and non-structural factors. Dissipation and damping capacity can have a significant influence on the complexity and cost of the structural connection.

3.3. Finite element modelling strategies: structural elements and connections

Finite element (FE) modelling is a fundamental tool to predict the structural response of a building. For Cross-Laminated Timber (CLT) structures, there are two main approaches to schematize CLT panels: Frame model (Mestar et al., 2020) and 2D orthotropic shells model (Rinaldi et al., 2021). Generally, mechanical connections govern the lateral response of timber structures and are modelled in FE analyses by using link elements or springs depending on the type of seismic analysis and the constitutive law implemented. In the case of taller buildings, the biaxial behaviour of connections should be considered, (D'Arenzo et al., 2021). In particular, it is possible to adopt a biaxial behaviour with a quadratic interaction relationship between tensile and shear loads (Izzi et al., 2018).

3.4. The role of floor diaphragms

The flexibility of floor diaphragms is an important property of timber structures that should be carefully considered during the design stage since it affects the load distribution between shear walls, bracing or cores, as well as adding to local deflections inter-storey drift (Moroder et al., 2014). The flexibility of the floor diaphragm is generally ruled by the slip between panels, which compose this structural element. Hence, the stiffness of the connections used to join together the different panels represent the key influencing parameters for the flexibility of the floor diaphragm (D'Arenzo et al., 2019).

3.5. Interaction of structural elements

The three-dimensional behaviour of the building can influence the lateral response of shear walls. In this respect, the perpendicular walls play an important role, yet typically, they are not considered in practical design. The effects of the perpendicular walls were found in several studies and also in several experimental campaigns on full-size LFT platform buildings to be significant (Van De Lindt et al., 2010, Tomasi et al., 2015). Additionally, the stiffness of the wall-to-floor connections between floor diaphragm and shear walls strongly influences the behaviour of multi-panel CLT shear walls (Tamagnone et al., 2020).

WG3.SG1.05

Standards, Codes and Guidelines

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1. Introduction

Regarding tall wood buildings, there has been a growing interest in construction above eight stories tall over the past 10 years, such as the 18-storey building "Mjøstårnet" in Norway and the 24-storey building "HoHo Wien" in Austria. This report summarises research on standards, codes and guidelines for tall timber building seismic design. Additionally, the limitations are highlighted for further investigations.

2. State of the art

2.1. Standards and guidelines

Eurocode 8 (EC8) was developed to establish harmonised technical rules and to achieve uniform levels of safety in the field of seismic design of structures. The current version of EC8 provides only six pages of specific rules for new timber buildings in Section 8 of EN 1998-1. Due to the growing use of timber in the construction sector, the provisions for timber buildings in EN 1998-1 were markedly extended and a dedicated chapter was introduced in EN 1998-3. The main updates of EN 1998-1 (now prEN 1998-1-2) include the introduction of new wood-based panels such as CLT, revised definitions of the structural types according to the behaviour under seismic actions, a new safety format for seismic verifications, a new definition of the behaviour factor q, new ductility rules for dissipative zones, capacity design provisions and overstrength factors, and detailing rules for all structural types. Other standards and guidelines around the world are also listed in Table 1.

Table 1: Standards and guidelines for seismic design of tall timber buildings

Standards and guidelines	Region	Specification and major updates
the International Building Code (IBC, 2021)	US	1. New construction types (IV-A, IV-B, and IV-C). 2. It allows mass timber buildings up to 18 stories, and greater allowable areas.
National Building Code of Canada, (National Research Council Canada, 2020)	Canada	1. Mass timber gravity system can be built up to 12 stories. 2. The lateral load resisting system (LLRS) system can consist of platform framed CLT shear walls up to 30m height in low seismic areas and 20m height in high seismic areas. 3. The design provisions for this LLRS are provided in CSA O86 (2019). 4. Some guidance is provided in the Technical Guide for the Design and Construction of Tall Wood Buildings in Canada (FPInnovations, 2020)
CNR DT 206-R1/2018	Italy	1. It includes capacity design rules necessary for achieving a dissipative behaviour. 2. Two ductility classes (high and medium) are allowed. 3. Behaviour factors values are specified as a function of the building typology. 4. No limit on the number of storeys.
NZ Seismic Design Guide (WPMA)	New Zealand	It summarises the seismic design rules in the forthcoming timber standard AS/NZS 1720.1 such as capacity design and overstrength.

2.2. Performance-based design methodologies

The rapid growing of tall timber buildings has not been accompanied by immediate standards updating. In addition, performance-based design (PBD), different from the force-based design (FBD) in current design codes, may provide a more proper assessment for the seismic design of timber buildings. Thus, PBD for timber structures as listed in Table 2 has been developed as an alternative.

Table 2: Performance-based design of timber buildings

LLRS system	Research
Wood frame buildings	Pang and Rosowsky (2009)
Glulam timber frame buildings	Zonta et al. (2011)
Timber-steel hybrid structures	Di Cesare et al. (2019) Teweldebrhan and Tesfamariam (2022)

In the PBD, the definitions of yield points and ultimate failure points were found to be inconsistent among different mass timber LLRS systems, which makes it difficult to compare the results from different tests, such as the ductility of structures.

2.3. Force reduction factor for FBD, and safety factors

To reflect the energy dissipation, the ductility characteristics, and the dependable portion of reserve strength in the LLRS of the buildings, the use of the force reduction factor (FRF) is specified by most building codes for the FBD as an alternative to full dynamic analysis. It is also called behaviour factor q, response-modification factor (RMF) and force modification factor (FMF) in Eurocode, US codes and Canadian codes, respectively. Typically, the FRFs are given for each LLRS and diverse values are provided by different design codes. Table 3 lists research on FRFs for multi-storey timber-related systems.

Table 3: Research summary on force reduction factor (FRF)

LLRS system	Research	Results
CLT buildings with light-gauge hold downs	Ceccotti et al. (2016) Sustersic et al. (2016)	q factor = 2 and 3 for single monolitic and coupled (segmented) CLT shear walls q factor = 2 and 3 for buildings made with monolithic and segmented CLT walls
	van de Lindt et al. (2022)	RMF=3.0 for CLT shear wall systems with 2:1 or mixed aspect ratio panels up to 4:1; RMF = 4.0 for CLT shear wall systems made up of only 4:1 aspect ratio panels (following the FEMA P-695 procedures)
Timber-steel hybrid structures	Zhang et al. (2015)	ductility factor = 5.0
	Chen and Chui (2017)	FMF = 2
	Khajehpour et al. (2021)	FEF = 6.0 (following the FEMA P-695 procedures)
Timber-concrete hybrid structures	Tesfamariam et al. (2021)	FEF = 3.0 (following the FEMA P-695 procedures)
Post-tensioned timber structures	Sarti et al. (2017)	RMF = 7.0
	Pei et al. (2019)	RMF = 6.0

Eurocode 5 provides safety factors for solid timber, engineered wood products, plates, and connections. The revision of Eurocode 5 will also provide the partial safety factors of new engineered wood products such as CLT. Eurocode 8 refers to Eurocode 5 for the partial safety factors to be used in seismic design of non-dissipative structures, whereas the partial safety factors for accidental design situations (generally unitary) are prescribed for dissipative structures.

3. Conclusions

Although significant research efforts have been put into the standardisation of mass timber LLRS, some challenges remain and require further investigations.

1. Although a complete revision of the timber section of Eurocode 8 is in place, some issues such as the design of hybrid buildings with different LLRS at the same levels or superimposed still have to be resolved.
2. Other methodologies such as PBD can be a complement to current standards, but consistent definitions are still required for the wide application.
3. Although innovative mass timber LLRS showed enhanced structural performance through testing, design parameters of these LLRS such as FEF and safety factors have not been verified by codes through a rigorous procedure (e.g. FEMA P695). In addition, the parameters are usually code-dependent, so the derived values are not directly transferable to different codes.

WG3.SG1.06

Case Studies

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1. Introduction

Tall Timber Buildings (TTBs) are becoming increasingly common around the world (Krötsch & Müller, 2018, Kuzman & Sandberg, 2016, Kuzmanovska et al., 2018), and their seismic design presents new challenges to structural engineers (Demirci et al., 2019, Stepinac et al., 2020, Moroder, 2016). Therefore, this section is dedicated to the analysis of several existing TTBs (based on idea of Salvadori, 2021), selected as Case Studies.

A comprehensive overview can be found also in Svatoš-Ražnjević et al. (2022), who examined the range of typologies and morphologies in current multi-storey timber construction in terms of structural and material aspects. The main objective of this contribution is to find and compare different features of TTBs (i.e., seismic force resisting systems, design strategy, and analysis models) developed by structural engineers to overcome design (calculation) or execution issues on seismically prone areas.

This classification and comparison could prove useful in formulating a handbook or standards section for TTBs. To achieve a simple but exhaustive analysis for each TTB case study, a data sheet template was designed. The latter is divided into different sections dealing with the main seismic design parameters. A complete register was prepared for each case study, but in the following (two-page State-of-The-Art Report) only some relevant aspects are discussed in depth: the location, the height/tallness, the lateral force resisting system (LFRS), the design strategy, and the building analysis model.

For the most significant parameter, the related part of the data sheet is given, where some values are shown as examples (in this STAR, the data sheet of Viale Giannotti in Florence is given). The complete data sheets and the description of the parameters are included in the Annex A.

2. Parameters and Information reported in Data Sheet

2.1. Location and Seismic Data

Location and Seismic data are provided in order to identify site conditions and seismic action so that researchers and designers can immediately understand the seismic demand and whether they are relevant to the design process (Table 1). In addition, the behaviour factor (q-factor) used in the analysis of the building is also provided.

2.2. Height and Tallness

Criteria need to be established for classifying a building into low-rise, mid-rise, and high-rise subcategories, for example, depending on the number of floors (Foster et al., 2018). Standardization of the various classification methods described in the literature and clear definition of each subcategory is essential to provide an overview of the existing TTB. Tallness and height are generally not the same thing. Height is objective; it is a measurable property of a physical object. On the other hand, tallness is subjective; it is a description of a physical object that implies some form of contextual reference (Foster et al., 2016).

2.3. Lateral Force Resisting System (LFRS)

The LFRS can be divided into hybrid and timber-only systems. The hybrid systems, especially where lateral forces are transferred to steel or concrete structures (cores), can be designed and built with current knowledge, while the timber-only systems require special high-performance connections and new design methods (Moroder, 2016).

Table 1. Information in the fact sheets on the lateral force resisting system.

7. Lateral Force Resisting System (LFRS)					
Reinforced concrete slab and wall (Basement) Floors 1 to 6: 5-layer spruce/pine CLT wall panel (100mm to 180mm thick) ETA-14/0349 5-layer spruce/pine CLT slab panel (140mm to 180mm thick) ETA-14/0349					
7.1. Cores	n.	-	Yes		~~No~~
			Side	Center	
7.2. Connections					
All CLT elements are connected to each other and to the foundation by use of steel plates and screws.					

2.4. Seismic Design Criteria

The Standards used for the design and verification of the building are given to explain the calculation methods, loads, safety and over-strength factors, etc. used by the designers. Similar buildings may have significant differences due to the Standards adopted.

Table 2. Information in the fact sheets on the seismic design criteria.

9. Seismic Design Criteria		
9.1. *Reference Standards*		
Eurocode 1995-1-1; Eurocode 1998-1-1; Italian National Standard (NTC 2018)		
9.2. *Capacity design*	~~Yes~~	No
9.3. Coincidence of the center of rigidity and the center of gravity	~~Yes~~	No

2.5. Analysis model

It is important to understand how the designers modelled the buildings and what modelling strategy they used for timber elements, connections, and other structural elements of the building. Project analyses could provide insight into how designers resolved critical issues and what technical solutions they chose. From the analyses of some case studies, it is possible to define the lateral seismic loads acting on TTB and especially internal forces on connection systems (as a function of location, number of floors, LFRS, dynamic features avoiding/reducing resonance response of TTB).

Table 3. Details in the fact sheets on the building analysis model.

10. Analysis Model	
10.1. Model Description	FEM:2D shell elements (mesh of 0.5mx0.5m)
10.2. Analysis Software	SAP2000
10.3. Seismic Analysis	Modal analysis

WG3.SG1.07

Interactions and Conflicts in Holistic Design

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1. Introduction

Building design is a complex, multidisciplinary engineering activity that involves making difficult trade-offs to balance competing objectives such as safety, reliability, performance, and cost. The design of a typical building involves the collaboration of many different disciplines – architecture, civil engineering, building services, etc. – for a relatively short period of time compared to the operational phase of the building. Each designer makes decisions based on design requirements, constraints, and inputs from other disciplines. Due to the fragmented nature of knowledge, no single professional has all the knowledge needed to design a complex facility. Although many building designers still work in parallel and independently, using different engineering tools, the benefits of collaboration are widely recognised (Fruchter, 1999, Lattke & Hernandez-Maestschl, 2016, Leoto & Lizarralde, 2019, Santana-Sosa & Fadai, 2019) including optimising functions, minimising costs and reducing errors.

Good holistic design cannot be achieved by focusing on a single design segment, as each issue can pull the project in a direction that may appear regressive to the other segment. It is often argued that integrated design is an effective way to improve collaboration in construction projects. Unlike the traditional silo-type and linear design process, integrated design is based on early stakeholder engagement and a holistic approach to project decision making. When designing a building with timber, the specific transfer of know-how between timber specialists or contractors and structural engineers or architects should take place earlier than for other structures, especially if they do not have previous and extended experience with timber construction. Ideally, on-site assembly strategies and off-site production systems should be considered at the design stage, allowing for an efficient workflow later on. Designing timber structures, therefore requires a more detailed approach and knowledge concerning, among others, material properties and structural behaviour, since all requirements related to fire, sound, moisture and thermal protection are integrated into the structural layer. At the same time, all disciplines, i.e., architectural, structural, mechanical, electrical, and plumbing (MEP), need to be coordinated and integrated in the design phase, as openings for MEP should be created at the factory and changes at the construction site should be avoided.

Current approaches to collaboration in practice often focus on integrating and managing multiple models from multiple designers. Building Information Modelling (BIM) plays an important role in facilitating collaboration. BIM provides the ability to electronically model and manage the large amount of information contained in a construction project, from conception to completion. In the construction design process, changes and modifications are inevitable even in the contemporary BIM approach, where it needs to be ensured that designers have an up-to-date version of the model.

2. Interactions and conflicts

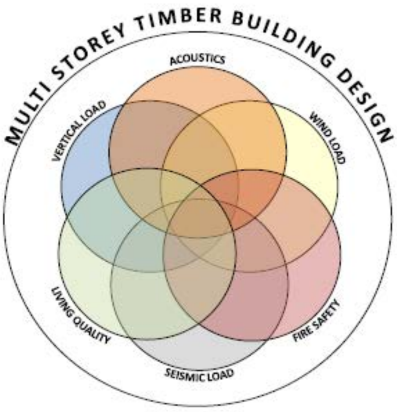
The collaboration and interaction of the various stakeholders (i.e., architects, engineers, contractors etc.) in the design of large timber buildings is often not clearly structured. Practical experience with prefabricated timber buildings shows that specific knowledge of production planning and methods for off-site timber construction comes too late, resulting in changes, problem solving, pressure and additional labour that are usually unpaid (Lattke & Hernandez-

Maestschl, 2016). Therefore, the design of taller timber buildings should be done with intensive collaboration between the members of the design team in the early stage (Aberger et al., 2018).

A fundamental conflict arises from the requirement to achieve structural safety with an optimized (cost-effective) design. Structural optimization based on cost efficiency may conflict with end-user comfort (Stepinac et al., 2020). One such example is the sound insulation of flanking noise and the lateral stability of timber structures. The principles of sound insulation currently applied to timber buildings are in complete contradiction with the design requirements resulting from wind or earthquake loads (Azinović et al., 2021). The acoustic demands decouple elements to limit the transfer of noise, while earthquake & wind requirements tie them together rigidly to resist lateral loads. Another example is the wind serviceability design where a higher mass is needed to reduce building vibrations (Malo et al., 2016). In some cases, therefore, additional mass is intentionally added to the structure. However, this mass also potentially increases seismic forces. There are also collisions between the desire to keep timber visible for human comfort and to meet fire safety and acoustic requirements (Buchanan, 2016).

However, conflicts in timber buildings can also arise due to different structural requirements, such as seismic design and robustness. Both focus on capacity based design and require connector ductility, but within different connection lines. Seismic design also needs to resist many load reversal cycles, whereas this is not essential for robustness.

The list of different type of conflicts can be continued, and it becomes even more challenging when you considering all the phases that a building goes through: design, construction, use, and finally demolition and recycling (Sandin et al., 2022), which is an important part of how sustainable buildings need to be designed for the future (Campbell, 2018). Šušteršič et al. (2021) summarized the possible conflicts that can arise in the multi storey building design (Figure 1) that effect both the load resisting and serviceability criteria of a building.



INTERACTIONS + positive - negative N neutral	VERTICAL LOAD	WIND LOAD	SEISMIC LOAD	FIRE SAFETY	ACOUSTICS	LIVING QUALITY
VERTICAL LOAD		+	-	-	+	N
WIND LOAD	+		+	N	-	N
SEISMIC LOAD	-	+		N	-	N
FIRE SAFETY	-	N	N		+	-
ACOUSTICS	+	-	-	+		-
LIVING QUALITY	N	N	N	-	-	

Figure 1: Interaction of a few different building design fields and their inherent collisions, either positive or negative, that need to be resolved for multi-storey taller timber buildings [from Cost Action CA20139 MoU].

3. Conclusions

Since generally proven solutions to such conflicts in design are not available in codes or standards, it is usually up to the design teams – assuming they have the appropriate knowledge and experience – to find solutions that can at least partially satisfy all parties. A holistic design must be guided by the technical requirements of the various disciplines, which should be weighted and hierarchized, taking into account the various interactions that result from a variety of objectives such as safety, reliability, performance, and cost. In practice, a designer must rely on his ability to make decisions based on calculations, but it is up to his talent to have a holistic approach to the requirements that ensure better design, construction and use.

WG3.SG1.08

Comments and Questions COST Action Helen Meeting Gothenburg

This chapter lists the questions asked and comments given during the COST Action Helen meeting in Gothenburg on the 4th and 5th of October 2022.

1. Questions

May the performances of timber connections subjected to cyclic loads change due to durability issues and/or additional fire loads?

Answer during event: majority of research on the cyclic behaviour of timber connections has been primarily focused on new elements subjected to cyclic loads. Recent studies have shown that the mechanical performances of the connections are influenced by thermal sources, and this is expected to be an issue for cyclic performances as well. Limited information is available on how durability issues (such as moisture content) may influence the cyclic performances of the connections.

How adhesive connections behave under seismic loads?

Answer during event: Adhesive connections have generally high mechanical performances, however, characterized by brittle failure mechanisms. For this reason, in seismic design analyses, they are often capacity designed and their post-elastic behaviour is not exploited.

Why different inter-storey drifts should be suggested for tall and mid-rise buildings?

Answer during event: Inters-torey drifts are generally used in Performance Based Design (PBD) to control the damage of structural and non-structural components of buildings subjected to low intensity earthquakes, and thus for serviceability limit state (SLS) design. The inter-storey drift is the sum of two contributions: i) displacement due to the cumulative rotation, which does not induce any damage, and ii) racking deformation, which induce damage. While in mid-rise buildings the inter-storey drift is mainly due to the racking deformation of the resisting system, in tall buildings the inter-storey drift accounts both displacements due to the cumulative rotation and racking deformations. Due to the “additional” displacement given from to the cumulative rotation of tall buildings, which does not induce damages, different inter-storey drift limits should be considered for tall timber buildings.

2. Comment

A member indicated that first topic of SG1 on *Seismic Load Resisting Systems* may have interactions with WG1.

Part 2

Fire

Sub Group (SG) 2

WG3.SG2.01

Building Regulations

Daniel Brandon, RISE (Sweden); **David Barber**, Arup (Australia)

1. Suitability of building regulations for taller mass timber buildings

Regulations to ensure fire safety in buildings differ vastly among countries. The most extensive global overview of fire safety regulations for buildings with timber structures is given by Östman (2021). The overview focusses on regulations regarding (1) the potential for lining materials to contribute to the development of a fire (for example by reaction-to-fire classes), and (2) fire resistance. However, in contrast to other combustible lining materials, mass timber is relatively thick and can contribute to the fuel of the fire for periods long after the development phase. This contribution can be increased by glue line integrity failure (i.e. fall-off of glued lamellas), fall-off of fire protection and significant charring behind fire protection (LaMalva and Hopkin, 2021). The fuel contributions of mass timber can lead to prolonged fires, which reduces the likelihood of the building to survive burnout scenarios (in which fire suppression and sprinkler suppression are unsuccessful).

Even though many building regulations do not explicitly require a building to survive burnout scenarios, analysis of background documents identified that the ability of conventional structures (with limited combustible materials) to withstand burnout was, at least in some countries, the underlying performance goal of certain fire resistance requirements (Brandon et al. 2022). Another performance goal for taller buildings (usually up to approximately 8 floors) identified in the study was a goal to contain the fire to a limited building part and allow enough time for fire service intervention.

Ensuring a building can withstand burnout cannot be done using reaction-to-fire classes and fire resistance requirements alone. Most building regulations have not been adjusted to meet such performance goals also with mass timber structures. A few exceptions are detailed in the next section.

2. Building regulations adjusted for mass timber structures

The building regulations in only a few countries (e.g. USA, Canada, Australia) have been significantly adjusted for the recent revolution of mass timber structures. These regulations involve different measures to limit or prevent possible effects resulting from the involvement of mass timber, such as increased fire duration and/or fire exposure, smoke development, risk of flashover, external façade exposure. Often additional regulations are in place to limit the extra sensitivity to fire spread through details such as cavities and connections. Requirements regarding automatic water-based fire protection and fire safety during the construction phase are also in place. Table 1 indicates such regulations for the USA, Canada and Australia. The different performance goals vary from restricting the involvement of mass timber (e.g. IBC 2021, type IV-A), to surviving burnout scenarios (e.g. IBC 2021/G147-21, type IV-B & 2020 NBCC), and containing the fire to allow enough time for successful fire service intervention (IBC 2021, type IV-C & NCC 2019 Type B and C).

Table 1: Building regulations in the USA, Canada and Australia

Country	United States				Canada	Australia
Building Code	**IBC 2021**			**G147-21**	**2020 NBCC**	**NCC 2019**
Building class	Type IV A	Type IV B	Type IV C	Type IV B	Encaps. MT	Type B or C
Height	≤18 floors	≤12 floors	≤6, 8, 9 floors	≤12 floors	≤12 floors	<25m
Required Fire resistance (FR)	flr. 120 min roof 90 min **rest 180 min**	Roof 60 min, **rest 120 min**			flr. 120 min	60, 90 or 120 mins, depending on use and height
Required fire protection	max. of - 80 min - 2/3 * FR eg. 3x 15.9 mm Type X, 1"layer on floor	max. of - 80 min - 2/3 * FR. eg. 2x 15.9 mm Type X, 1"layer on floor	Not dependent of construction type	max. van: - 80 min - 2/3 * FR. eg. 2x 15.9 mm Type X, 1"layer on floor	50 min eg. 2 x 12.7mm type X gypsum, 38mm concrete on floor	Above three flr, 30 mins protective covering to all timber (1 x layer 16mm fire rated plasterboard). Top side of floor can be Unprotected
Maximum exposed surface area	0%	20% ceiling or 60% of 2 walls	100%	100% plaf. of 60% van 2 wanden	35% of all walls	Above 3 floors, timber is protected
Distance between exposed surfaces	Not applicable	4.6 m between exposed surfaces	No limitation	4.6 m between exposed surfaces	Exposed surfaces same direction	Only topside floor can be exposed >3 floors
Resist glue failure	Demonstrated to pass tests of PRG 320 (2019) Annex B & 6.2.1-b					Not addressed
Limitation of fire development	NFPA 13 sprinklers >36m, 2nd water supply & 100% encapsulation	NFPA 13 sprinklers >36m, 2nd water supply & 100% encapsulation	NFPA 13 sprinklers	NFPA 13 sprinklers >36m, 2nd water supply & partial encapsulation	Sprinklers & partial encapsulation	Fully sprinkler protected building & >3 flr, all surfaces protective covering
Limitation fire spread through intersections	Fire sealed with ASTM C920 sealant, or ASTM D3498 adhesive				Independent of meterial	16mm fire rated plasterboard protection to MT surfaces
Limitation fire spread through cavities	No exposed wood in hidden voids, non-combustible protection layer is required				· fire stops · cavity ≤ 20 m	Fire stops for light frame
extinguishing facilities	· >36m, 2nd water supply · > 4 flr., stand pipe				> 3 floor., Standpipe	Sprinkler protection throughout building
Fire Safety during construction	· Stand pipes and water supply · >6 flr.: gypsum on all floors except for the 4 upper floors before erecting new floors · hydrants with additional water flow requirements				Hydrants with specific waterflow	No specific additional requirements
Facade requirements	Non-combustible & 40 min protection between façade and mass timber, for example . 15.9 mm type X gypsum				≤6 flr, ≥90% non-comb. lining or ULC-S134 tested	No additional lilmits for timber buildings. Combustibility restricted above 3 floors

WG3.SG2.02

Real fire exposure

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1. Introduction

In comparison to common non-combustible high-rise buildings, when timber is used as a structural material it can significantly alter the compartment fire dynamics. This section aims to describe the real fire behaviour in compartments with (partially) exposed timber (e.g., engineered wood products (EWP)), and protected timber elements that may contribute to the fire if their encapsulation fails. Experimental findings to date are summarised, and design challenges are highlighted for the growth phase, fully-developed (post-flashover) phase, and cooling phase of a realistic or 'natural' fire.

2. Thermal degradation of timber

Depending on the specific species, wood is generally composed of cellulose (40-55%), hemicellulose (15-35%), lignin (18-40%) and other minerals and extracts (Neugebauer 2019). As other construction materials, wood is subjected to both physical and chemical changes at elevated temperatures. At temperatures above 100°C, the water and moisture within wood move, diffuse and/or evaporate. Wood typically starts decomposing and releasing combustible gases for temperatures above 200°C, known as pyrolysis. Above 280-300°C, residual carbonaceous char is formed upon pyrolysis, and in the presence of oxygen, the wooden char further degrades in oxidation reactions, typically in the temperature range 400-500°C (Browne 1958). Accordingly, the thermal decomposition of wood alters its mechanical properties. Compared to ambient temperature conditions, wood stiffness and strength reduces for relatively low temperatures, and the wood load-bearing capacity is considered null above charring temperature, assumed equal to 300°C (EN 1995-1-2:2004).

3. Fire growth and available safe egress time

The time to untenable conditions in a compartment can be shortened if timber becomes involved early in the fire. This regards the development of compartment temperatures (Li et al., 2015; Su et al., 2018a), and can also include toxicity (Hull et al., 2016) and visibility. Flashover in exposed timber compartments has been observed to occur earlier than in non-combustible compartments (Li et al., 2015; Su et al., 2018b), exacerbated by the area, number and position of exposed surfaces. Exposed timber ceilings in large open-plan compartments can promote much faster fire spread rates and transition to fully-developed fire conditions once the combustible ceiling ignites (Gupta et al., 2021; Kotsovinos et al., 2022; Nothard et al., 2022).

Active fire protection systems can in many regulatory frameworks be used as a trade-off to reduce other fire safety provisions, such as the fire resistance of structural elements or compartmentation. In practice, sprinklers are often provisioned to protect taller buildings built in timber to control any occurring fire and prevent fire growth and spread (Östman et al., 2022), and hence effectively lower the risk of untenable criteria (Frangi and Fontana, 2005; Zelinka et al., 2018). Experiments with exposed CLT surfaces show that the HRR from a compartment fire can be significantly reduced through sprinkler systems compared to non-sprinklered scenarios (Zelinka et al., 2018). However, sprinklers are not 100 % effective, and potential failures to activate the system or control the fire early enough can lead to total suspension of their operation, in which case a structure would have the same protection as with no sprinklers present. Therefore, the use of sprinklers to relax other safety provisions must follow a well-reasoned risk assessment to avoid compromising building safety.

4. Fully-developed fire dynamics

A fire may be defined as fully-developed once it has reached a quasi-steady peak state in which its size is constrained by either the availability of oxygen (under-ventilated compartments) or by the availability and configuration of fuel (well-ventilated compartments) (Thomas et al., 1967; Torero et al., 2014).

During the fully-developed phase, the additional fuel load from burning timber elements will increase the total heat release rate (HRR) of the fire (Crielaard et al., 2019; Gorska et al., 2020; Hadden et al., 2017; Li et al., 2015; Su et al., 2018a). In under-ventilated compartments, this excess fuel will combust outside of the compartment, with little impact on the amount of heat generated internally. In well-ventilated compartments, ignition of wooden surfaces will increase the internal HRR, increasing temperatures and heat fluxes within the compartment (McNamee et al., 2021), and potentially causing a travelling fire to transition to flashover (Gupta et al., 2021; Kotsovinos et al., 2022; Nothard et al., 2022).

In either case, the configuration of exposed surfaces may alter the flow fields within the compartment, resulting in highly non-uniform temperatures or heat flux distributions (Gorska et al., 2020; Pope et al., 2021).

Exposed timber has also better insulative properties compared to concrete or masonry, resulting in higher heat accumulation and possibly higher fire temperatures in compartments (Bartlett et al., 2020; Lange et al., 2020; Węgrzyński et al., 2020).

Burning timber surfaces may also extend the duration of the fully-developed period significantly if self-extinction of the timber surfaces is not ensured. Char fall-off and delamination, failure of encapsulation, or excessive heat feedback may all result in continued burning until failure of the compartment (Bartlett, 2018; Hadden et al., 2017; McGregor, 2013; McNamee et al., 2021; Medina Hevia, 2015; Pope et al., 2021).

The duration of the heating and cooling phases, and the progression of the thermal wave beneath the char layer (Gernay, 2021; Wiesner et al., 2021a), define the structural performance of timber elements under real fire conditions.

In engineering standards, the char layer depth is specified by *standard fire* exposure and pre-defined charring rates (CEN, 2004). Considering variable fire durations and severity in reality, actual charring rates often differ from such values.

4.1. Exposed wood – Fire induced delamination and char fall-off

When some EWPs are exposed to fire conditions, the adherent (timber) and the adhesive do not deteriorate at the same rate, which can lead to unpredictable failure modes, both in timber and the bond line region (Emberley et al., 2017b; Frangi et al., 2004), seen most prevalently in CLT.

Such failure modes for CLT are (i) char fall-off and (ii) fire induced delamination. Char fall-off appears in any part of the charred cross section. Fire induced delamination, also known as glue/bond line integrity failure (Hopkin et al., 2022), appears in the proximity of the bond line at temperatures lower than the timber pyrolysis temperatures. Both failures initiate a change in fire dynamics and heat transfer (Bartlett et al., 2017; Emberley et al., 2017c; Frangi et al., 2009;

Hadden et al., 2017; Su et al., 2018a), but delamination also influences the loss of structural capacity and fire dynamics (Wiesner et al., 2021b, 2020).

Both failures can be influenced to a limited degree by edge bonding and by increasing the thickness of the first lamella. Different types of adhesives also exhibit varying delamination and char fall-off behaviours and can improve performance (Brandon and Dagenais, 2018; Čolic et al., 2021; Čolić, 2021; Crielaard et al., 2019; Frangi et al., 2004; Hopkin et al., 2022).

4.2. Encapsulated wood – Failure of encapsulation

Failure of encapsulation is defined by either a loss of mechanical integrity or inadequate thermal insulation (Xu et al., 2022) and is usually one or a combination of (i) insufficient thickness of the encapsulation materials, (ii) insufficiently covered compartment area (i.e., fuel load is increased by exposing the timber surfaces), or (iii) mechanical failure of the encapsulation joints and fasteners (Chorlton et al., 2021).

Fire resistance of plasterboards is currently tested under the standard fire curve, but they are known to be sensitive to the heating rate, and fail faster in most fully-developed compartment fires (Brandon, 2018). Charring of wood behind encapsulation boards is allowed based on fire resistance requirements alone. However, in real fires, significant charring due to smouldering behind insulating boards is likely not to stop automatically even after the compartment has cooled down, and can lead to char depths greater than those of exposed timber in the long run (Su et al., 2018a).

A challenging aspect is that the failure of encapsulation during the cooling phase may lead to continued burning, or re-ignition of the timber structure and possible subsequent re-emergence of a fully developed fire stage (Su et al., 2018a, 2018b).

Intumescent coatings can also be used as a passive fire protection of timber elements while maintaining their aesthetic value. However, effectiveness can vary greatly depending on the heating conditions, and small differences in applied thicknesses may have large effects on the resulting protection (Hartl et al., 2020; Hasburgh et al., 2016; Lucherini et al., 2019).

4.3. Exposure to facades and external objects

The additional combustion energy of mass timber that is involved in a fire can lead to increased exposure to facades and external objects, especially in ventilation controlled fires (Brandon and Östman, 2016; Frangi and Fontana, 2005; Hakkarainen, 2002).

The flame height and thermal exposure to the facade is, among other things, dependent on the surface area of exposed timber, and the ventilation opening dimensions, (Bartlett and Law, 2020; Gorska, 2020; Sjöström et al., 2021) and have been performed with façade measurements for statistically slender and small openings to get exposures on the severe end of the spectrum. Models predicting flame height are published by Hopkin and Spearpoint (2021) and Gorska (2020) (Gorska, 2020; Hopkin and Spearpoint, 2021). Many national standard façade fire tests, do not induce the same level and duration of exposure as can be expected in bad-case fire scenarios (Sjöström et al., 2021).

Currently, fires jumping from floor to floor in timber buildings can be prevented by severe architectural constraints (Law and Kanellopoulos, 2020) or fire resistance glazing, which is more significant if exposed timber is present.

4.4. Time-equivalency (use of classification fire resistance and k classes for PBD)

Time-equivalency methods are needed to enable the use of fire resistance ratings of products (e.g., fire separation walls, fire doors, fire sealants, penetrations) in a performance-based design approach, where it is infeasible to explicitly quantify the performance of all building elements under real fire exposure (Wade, 2019). “Equivalent time” indicates the duration of fire resistance testing required to induce the same structural damage as a defined duration of a specific design fire or real fire. However, ensuring a fire will fully stop (including residual smouldering) may require the involvement of fire-fighting services in the fire strategy, or full encapsulation of the timber structure. Such methods should account for the fuel contribution of the timber structure, which depends on the real compartment fire dynamics.

For timber structures, due to high uncertainties caused by knowledge gaps, experimental validation of such methods or extensive data derived from such experiments is needed, for accurate assessment through performance-based design.

5. Cooling phase fire dynamics

Once the moveable fuel load in a compartment has been consumed, the fire may decay sufficiently to allow the burning timber elements to decay through to flaming self-extinguish and burnout (Bartlett et al., 2017; Brandon et al., 2020; Crielaard et al., 2019; Emberley et al., 2017d; McGregor, 2013; Medina Hevia, 2015; Zelinka et al., 2018). If flaming self-extinguishment is achieved, the compartment will continue to cool rapidly in the gas-phase, but the effects of solid-phase heat-transfer and smouldering may be apparent over much longer timescales (Kotsovinos et al., 2022; Wiesner et al., 2022).

In contrast to compartments with non-combustible boundaries, timber compartments might never achieve 'burnout' under certain conditions, and may continue to burn long after the moveable fuel is consumed, depending on the area of exposed timber and the type of timber, such as CLT that delaminates. Burnout of timber compartments is considered to occur when flaming extinction (extinguishment) or glowing and smouldering extinction occurs. However, there is no general consensus on the definition of burnout (Schmid et al., 2021).

In any case, ensuring the conditions for flaming self-extinguishment of exposed timber surfaces is one step in designing for the eventual burnout of a compartment fire. This can be achieved when the external radiant heat flux onto the surface of the charring timber falls below a critical value that ranges between 30-50 kW/m^2 (Bartlett et al., 2017; Cuevas et al., 2020; Emberley et al., 2017d, 2017a; Terrei et al., 2021). Thermal degradation of the timber impacting strength will still occur after flaming self-extinguishment and needs to be accounted for.

The charred timber acts as a thermal insulator, and the critical heat flux criteria applies once the char layer thickness has reached a quasi-steady state, so it can be compromised by char fall-off or delamination that increases the heat transfer to the underlying timber (Bartlett et al., 2017; Emberley et al., 2017b; Medina Hevia, 2015; Su et al., 2018a). Once the moveable fuel load has been consumed, the residual thermal exposure to the exposed timber will be dominated by radiative and convective heat feedback from the other compartment surfaces. Consequently, the area and configuration of exposed timber surfaces must allow for the residual heat fluxes in the compartment to fall below the critical value for flaming self-extinguishment, noting that thermal degradation will still occur. This also requires that the integrity of encapsulation is maintained where installed (Gorska et al., 2020; Hadden et al., 2017; Medina Hevia, 2015; Su et al., 2018a; Xu et al., 2022).

The configuration of exposed timber surfaces may have a greater influence on the potential for flaming self-extinguishment than the total exposed area, since this will control the heat transfer between surfaces. For example, it may be safer to expose a ceiling than a wall, because the burning rate of the ceiling is lower (Brandon et al., 2020; Gorska et al., 2020). Ventilation, and the associated availability of oxygen, also has a significant impact during the decay phase for char oxidation, which can be an important process as the heat flux from combustion of the moveable fuel load decreases (Harmathy, 1978). Localized smouldering may continue for many hours following the cessation of flaming, even leading to failure of compartmentation or structural collapse without intervention (Kotsovinos et al., 2022; Wiesner et al., 2021a). This risk is associated with much longer timescales that allow for fire-fighting detection of smouldering, management, though once detected is relatively easy to extinguish. Therefore, specific fire-fighting strategies are needed for smouldering in concealed spaces.

WG3.SG2.03

High Structural Fire Performance Solutions

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1. Introduction

Engineered timber has been and continues to be chosen as the main structural material for taller and more ambitious buildings. This development imposes new load bearing demands on timber, both in terms of stress direction and magnitude. Both structural and fire safety engineers must critically evaluate technical issues arising from this development, to ensure levels of safety that are equivalent to those accepted for tall and complex buildings employing legacy materials (i.e. concrete and steel) for their structure. This section introduces and details the most pressing concerns that arise from a structural perspective for mass engineered timber buildings in case of fire.

2. Fire protection by non-combustible boards

Most research on passive fire protection cladding to timber is performed for gypsum boards. A comprehensive review of fire resistance tests has been performed by Just *et al.* (2010) to determine empirical relationships of gypsum based board performance for fire resistance calculations. Such a review is lacking for other types of non-combustible cladding. Insulation behind cladding can also contribute to the fire performance but can fall off once the cladding fails. Despite the significant effect failing protection can have on the fire performance, only one study has been found that compares the fire performance several fixing methods for protective cladding (Tiso, 2018).

3. Structural fire performance of timber elements

Taller building heights necessitate the use of engineered timber with increased cross-sectional dimensions for vertical load paths and of long-span, multi-span, and point supported beam and floor systems. One resulting issue is that some large members cannot be tested in existing furnace arrangements, causing a scarcity of data on their fire performance. Consequently, engineers must rely on engineering considerations to scale load bearing capacity for vertical load bearing members in fire. Existing tools for the assessment of load bearing members are either empirical (Li 1977) or use approximate explicit considerations of losses of mechanical properties to assess load bearing capacity during expected fire duration (König, J., & Walleij, L. (2000), Eurocode 5 (2009)).

The fire design of load bearing timber beams and floors can be use either the code prescriptive simplified calculation method (e.g. effective cross-section method from Eurocode 5 (2004)) or through advanced calculation methods which explicitly account for temperature induced loss of mechanical properties. The former has been shown to not be reliable for more complex structural systems, such as CLT, while the latter relies on knowledge of the overall thermal profile. The behaviour of engineered wood systems exposed to fire are also dependent on the type of connection used in the system (e.g. glued or mechanical connections). Elevated internal member temperatures can cause a reduction or loss of composite action due to a reduction in timber strength or adhesive performance (Klippel, 2014, Wiesner *et al.*, 2021a).

Columns and walls are usually subjected to large compression forces and timber mechanical properties are most affected in this mode of loading. As a result, large losses in structural capacity can arise during the cooling phase after a fire and further research is required to ensure that furnace results are appropriately applied to real fire exposure (Gernay, 2021, Wiesner et al., 2022).

4. Connections and penetrations

There a number of literature reviews for connections (Maraveas et al 2013, Audebert et al 2019, Brandon *et al.*, 2019) which indicate that most fire resistance tests of connections between glulam or sawn timber are not directly applicable to taller buildings because of the load direction and a fire resistance of 60 minutes or less, see (Figure 1). Higher fire resistance rated connections for glulam beam to column members are available (Barber 2017).

Frangi, (2001) and Fornather, (2003) indicated that a flow of hot gasses through small gaps can heat up the timber enough to start smouldering at connection and penetration interfaces, which eventually can accelerate burn-through. Recent fire testing has shown the use of intumescing seals can slow or prevent this issue (Barber et al 2022) Multiple studies of full-scale compartment tests indicated that wall-ceiling connections in CLT structures are sensitive to burn-through (Su *et al.*2018, Brandon *et al.* 2021). There is however no fire resistance test standard for such connections.

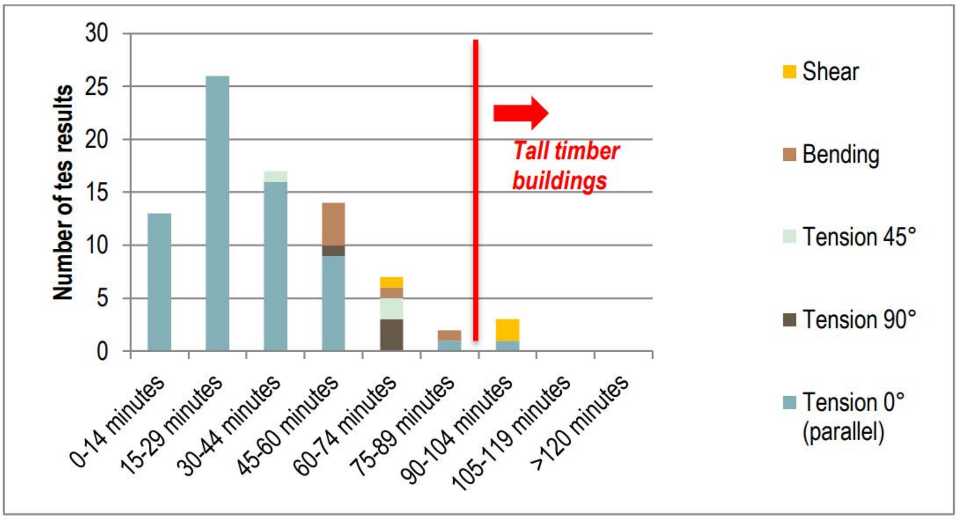

Figure 1: Overview of published fire resistance tests of glulam and sawn timber connections by load direction and fire resistance, from Brandon et al. (2019).

Buildings are separated by compartment walls and floors and penetrations in these fire barriers for electrical, mechanical, plumbing and structure should be minimised. Fire sealing a penetration requires a product tested and approved for use, typically with specific characteristics, level of performance and range of application (Werther et al 2012, Werther et al 2016). Although European fire resistance test standards require penetrations through non-conventional supporting structures such as CLT, only one publication was found that included results of such tests (Ranger *et al.* 2018).

5. Integrity failure of glue lines

Adhesives are used for face-bonds between layers, bond lines between components and finger joints within the components of engineered wood products. Thermal stability of the adhesives influences the fire performance of engineered wood products compared to solid wood products. The fire behaviour is influenced by the chemical composition of each adhesive (Clauss, 2011) as well as the rate of heating, applied loading, and transient moisture conditions (Wiesner et al., 2021b).

Previous research found that even within each adhesive group (PUR, MUF, MF, PRF, and EPI adhesives) significant differences in performance could be observed (Klippel, 2014, Frangi et al., 2004). The assessment of adhesive performance at elevated temperatures has been done at both small (Kleinhenz et al., 2021b, Zelinka et al., 2019) and large scale (Kleinhenz et al., 2021a, Brandon and Dagenais, 2019) and with varying heating and loading conditions – which has led to conflicting outcomes and interpretations (Čolić, A. et al., 2021). A global consensus on the appropriate testing and understanding of bond line behaviour is lacking.

6. Research Gaps

Taller and larger timber buildings pose additional fire safety design challenges for engineers, architects and fire and rescue personnel. These buildings often utilise larger open spaces and larger timber members are required to carry higher loads that arise from the increased size and ambition.

Previous timber research has often been focused on fire resistance testing and it is not fully understood how outcomes from simply supported conditions of single elements in a furnace can be extrapolated to longer multi span systems, point support situations and more complex connection systems with higher performance requirements than existing test results. The question of connection and load details is especially pertinent when considered for the combined action of earthquakes and fires – two statistically dependent events.

The additional complexity in capacity also extends to the individual components of the structural timber elements – namely, how their composite action can be maintained. This requires better understanding of how adhesive bond lines perform the aforementioned complex loads but also under different fire conditions.

WG3.SG2.04

Property protection

Carl Pettersson, RED Fire Engineers (Sweden); **Annette Riel**, CREE GmbH (Austria); **Joachim Schmid**, ETH Zurich (Switzerland); **Daniel Brandon**, RISE, (Sweden); **Chamith Karannagodage**, ETH Zurich (Switzerland)

1. Introduction

With the increase in size and height of timber buildings, property protection in the event of fire becomes more important. The resulting damage after a fire can be extensive if appropriate fire protection strategies are not in place. Damage can be fire-induced but also due to water used in fire-fighting operations or burnt-off contents and fittings. Property protection and post-repair after a fire also relate to the insurance prospects of a building, to which the insurability demands an analysis of how the building might perform against fire and material and function recovery RISC Authority (2022).

2. Fire protection strategies and robustness

There are different types of fire protection measures which can be categorised into passive or active fire protection, which in combination with a particular building are part of its fire safety strategy (Buchanan & Östman 2022). Encapsulation of timber structures with non-combustible protective boards is an example of passive fire protection preventing the timber structure from being involved in a fire event. Provided with sufficient encapsulation, the fire can be expected to behave more similarly to a fire in a non-combustible building structure. Active fire protection measures such as sprinkler protection rely on different components to operate sufficiently or operate at all and therefore need particular attention in order to ensure that their installation, commissioning as well as management and maintenance are carried out accordingly.

Several experiments have proven that an automatic sprinkler system, as well as a water mist system, are effective in compartments with exposed timber in walls and ceilings (Frangi and Fontana 2005; Zelinka 2018; Kotsovinos et al 2022; Ko and Nour (unpublished)). Garis and Clare (2014) indicate, based on a statistical study, that operating sprinkler systems reduce the extent of fire spread in a building independent of its construction materials.

Nonetheless, fire is a systematic exposure, which affects a potentially large number of elements simultaneously Schmid et al. (2021). This makes fire behaviours and scenarios very hard to accurately predict. It is therefore of great importance that the fire safety in buildings has extensive robustness in all aspects of fire safety measures. The failure of one measure or component should not lead to the complete failure of the fire safety strategy in the building, and protective layers are necessary to prevent extensive damage, see Figure 1.

The scenarios for robustness analysis shall challenge the trial fire safety design by disabling active and passive fire safety systems, or common resources one at a time INSTA TS 950 (2014). Structural robustness also needs to be considered and general approaches for evaluating the structural robustness can be found in Schmid et al. (2021).

3. Firefighting strategies

A modern timber building with a combustible structure introduces complexity and a set of different possible fire behaviours which create practical challenges for the fire service. If combustible structures in a building are involved in a fire, longer burning and fire spread through openings (windows) can be expected. Fire spread into cavities in walls, shafts, floors and ceilings with combustible materials (see Figure 2, left) may also impose problems for the fire service. The outcome of firefighting operations in complex buildings will therefore depend on the fire service experience, training, routines, capabilities and techniques to mitigate the damage (Torero 2021).

Limited research has been conducted to find the most effective approach to locate and extinguish fires inside combustible cavities (Hox en Saeter Boe 2017) and timber structures (Brandon *et al.* 2021).

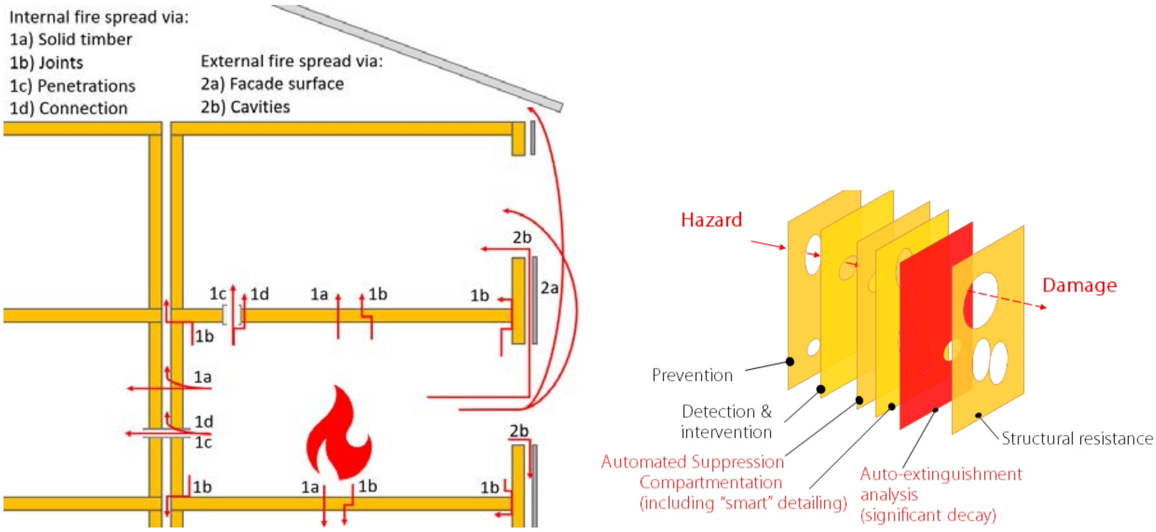

Figure 2: Left, potential paths of fire and smoke spread to be considered (information combined from Brandon et al. 2018); Right, visualization of fire safety elements to prevent from damage, modified from Schmid (2022).

4. Damage

Property damage resulting from fires generally results from the flame spread, smoke spread and extinguishment water and extinguishment activities. The influence of timber as a structural material on flame spread has been investigated in comparative studies with non-combustible building materials, by UK Dept of Communities and Local Government (2012), Garis and Clare (2014), Eriksson *et al.* (2016), Berg (2021), Brandon et al (2021b). The data indicated no statistically significant difference between the extent of flame spread in multistorey buildings in the US, Canada, New Zealand or Sweden. However, the further analysis did identify specific fire incidents where the presence of a timber structure was identified as a cause of excessive fire spread. Data from New Zealand indicated no statistical difference in the extent of water damage in terms of building areas affected (Brandon *et al.* 2018). However, data on the actual financial costs of these damages is missing.

Analysis of incident reports of a US database of high damage fires indicated that incidents with high levels of water damage were more frequently extinguished by the fire service than by sprinklers. Tests by Ko en Nour, (unpublished) analysed the water damage to exposed wood after sprinkler activation and concluded that connections between the floor and walls are sensitive to water damage. No published data on the influence of structural timber on smoke damage was found.

5. Post-fire repair

The repair of damaged components after a fire may be grouped into three main categories:

1. Non-structural repair, e.g. aesthetics or surface related repair;

2. Structural repair of parts of the components;
3. Structural repair by the exchange of components.

Typically, all categories are executed on site, which may require significant preparation (e.g. façade openings, bracing of the structure) of the work execution. Furthermore, the repair execution typically comprises the involvement of several professions (SCIUS Advisory 2020).

6. Property valuation

Publications from the scientific community in recent years have focused to a greater extent on mass timber. In comparison, US insurance companies address mass timber and lightweight construction in their publications (Hester 2022).

In a German publication from 2008, modifications of the underwriting evaluation criteria were still discussed with a focus on building class and fire resistance without mentioning or including water damage as a hazard (Stein 2008). Today, most publications on property protection also refer to the risk of water damage.

A recent white paper found that insurers lack knowledge, resulting in a lack of confidence in assessing the likely financial impact when a predominantly combustible building needs to be protected against fire (RISC Authority 2022). Furthermore, a trend toward "evacuation before collapse" and the blurring of the line between a collapse due to accidental damage and a collapse due to slower events as critical factors (RISC Authority 2022). It is important to know the golden rule of the provision of insurance for the people who deal with fire design and who do not, that is 'you can't insure what you can't quantify' (RISC Authority 2022). Insurers are rating the statistical likelihood of damage events taking place. Finally, the authors acknowledge long-lasting, trusting customer relationships that create the basis for reducing risk through collaboration using a mix of conventional and newer methods (RISC Authority 2022).

Our unmistakable recommendation to designers is to map the customer's design specifications to the relevant features (RISC Authority 2022) and track the insurance information requirements as presented in the reference.

Whether it makes economic sense to further reduce the extent of projected property damage could be analyzed by developing various concepts to support the client's profitability calculation. However, statistical analysis of firefighting and damage due to spread beyond the area of origin varies widely (Berg 2020, Brandon et al. 2018). One challenge is access to a complete data pool.

Underlining the urgency, a US/Canadian survey, that 20 people answered and 2 of them were project insurers, identified four information needs of the key influencer group "insurance and bonding", one of which is the need of more research on durability and historical damage (SCIUS Advisory 2020).

The report (SCIUS Advisory 2020) is missing "property loss" as a type of insurance commonly used in construction projects, which could be interpreted as the trust in building regulations by insurance in the US/Canada being very high. Suggesting that there is a need to investigate why and what can be done to increase this confidence in other countries as well.

7. Fire safety during construction

There is a difference in statistical studies on how to limit fire damage during construction. Most research and guidance are based on light timber frame construction. One example being that timber buildings are prone to much larger fires during construction (UK Dept of Communities and Local Government 2012).

Several guidelines have been developed for fire safety during construction Bregulla *et al.* (2010), the UK Timber Frame Association (UKTFA, 2008) and Just *et al.* (2016), mostly based on experience, reasoning and good practice.

In July 2021, the French Prefecture of Police and the Paris Fire Department issued the so-called "Doctrine Bois", which presented new rules for multi-storey wooden buildings higher than 8 m, however, these are not yet incorporated into any regulation. These rules require the provision of fire extinguishers on each floor, 180 m^3/h hydrants, a dry standpipe in buildings over 18 m, an automatic fire alarm system and an automatic water sprinkler (*DTPP* 2021).

Since 2017, the Structural Timber Association (STA) in the United Kingdom has recommended compliance with the "16 Steps to Fire Safety" on construction sites where timber is used as load-bearing elements, continuing to provide guidance to insurers in 2021 (STA 2021).

In 2022, a new international guide emphasizes the necessary quality of craftsmanship, trade coordination, assignment of responsibilities, and key immediate actions in case of fire. Uninstalled or inactive fire protection equipment during construction makes it necessary to explicitly coordinate construction-related emergency measures with the assembly sequences (Buchanan & Östman 2022).

WG3.SG2.05

Comments and Questions COST Action Helen Meeting Gothenburg

This chapter lists the questions asked and comments given during the COST Action Helen meeting in Gothenburgh on the 4th and 5th of October 2022.

3. Questions

What design measures are the result of large-scale exposed timber surface fire tests pointing to?

Answer during event: Effective measures are dependent on the compartment and the expected fire scenario. These can for example include protection of the walls, as recent studies show they can have more significant involvement in fires than ceilings. Furthermore, prevention of delamination of mass timber and failure of fire protective boards can be important.

Which research answers sprinkler failure? Did you include references?

Answer during event: A number of studies looked at the effect of sprinklers in specifically timber buildings. The most extensive work is performed by Professor Garris and studies Canadian fire statistics.

Does exposing the timber elements have any plus sides aside from aesthethic/architectural added value? If the consequence can be so severe would it not just be logical to ever expose them?

Answer during event: gypsum protection adds significantly to work load and costs. It also results in an increased carbon footprint. As timber is hygrospic it has a positive effect on room climate due to moisture buffering. Comfort and health benefits of having visible wood are often mentioned.

Are there studies that indicate the extent of fire spread is more an issue for tall or large buidings? I guess we should be much more careful with fire spread and related issues in tall buildings (along facades or internal gaps etc.)

Not discussed during event.

Does the fire group also have an approach to a cross-over holistic consideration e.g. fire & repair, adaptability, connections, durability?

Not discussed during event.

4. Comment

A member indicated a clash between people protection and fire protection regarding fire safety.

Part 3

Blast Loads

Sub Group (SG) 3

WG3.SG3.01

High-strain rate effects in timber members

Abla Krouma, University of Ottawa (Canada); **Christian Viau**, Carleton University (Canada); **Ghasan Doudak**, University of Ottawa (Canada)

1. Introduction

Mass timber constructions are on the rise due to sustainability concerns, rapid construction, and cost efficiency. Since 2009, the number of tall timber buildings, defined by the Council on Tall Buildings and Urban Habitat (CTBUH) as having at least eight stories, has increased to sixty-six buildings (Council on Tall Buildings and Urban Habitat (CTBUH), 2022). Along with the increase in market share of the construction industry, this brings forth an increase in potential exposure to accidental and intentional blast explosions, such as that from gas leaks and vehicle bombs, respectively. Understanding how wood behaves when under high strain-rates and having well-established mitigation strategies to minimize the risk of progressive collapse, is required to ensure that these novel structures remain safe to building occupants. During the last two decades, the behaviour of various wooden structural systems under blast loading has been studied through numerous experimental studies. While some studies were conducted using live explosive testing, such as (Weaver et al., 2018), shock tube testing, which allows for the simulation of the shock wave of a far-field blast explosion (i.e. planar shock front), has allowed elements, connections, and sub-assemblies to be investigated whilst obtaining relatively amounts of quantitative results, such as reactions, deformations, and deflected shapes (Côté & Doudak, 2019; Lacroix & Doudak, 2018d; Viau & Doudak, 2021). Other studies have generated high strain-rates using split Hopkinson pressure bar (SHPB) (Bragov & Lomunov, 1997) or conducted impact tests using drop-weight impact apparatus (Sukontasukkul et al., 2000).

2. Wood material behaviour at high loading rates

Early studies on small clear-wood specimens under HSR (i.e., greater than 0.1 s^{-1}) observed apparent increases in wood's material properties (e.g., Liska, 1950; Gerhards, 1977), confirming the viscoelastic nature of the material. As an organic material, HSR effects and failure modes were found to be affected by the direction of the load and the moisture content (Widehammar, 2004). Under impact bending tests, the high shock resistant specimen developed long and coarse splinters specifically on the compressive side, while the normal wood specimen failed in shorter and fibrous splinters that are longer on the tension side (Kollmann & Côté, 1968), while brittle wood specimens failed in cross grain tensile fracture at lower impact levels.

3. Behaviour of full-scale timber elements

Some of the earliest experimental research carried out on the effect of blast loads on timber structures was conducted on model full-scale light-frame homes subjected to nuclear blasts (Kimbell & Fies, 1953; Randall, 1961). Post-test observations revealed that the failure of these structures was heavily dependent on continuity in the systems and was most often initiated at the load-bearing studs, roof hangers, and boundary connections. During the last two decades, the behaviour of various wooden structural systems under blast loading has been studied through numerous experimental studies. While some studies were conducted using live explosive testing (Marchand, 2002; Oswald, 2005; Weaver et al., 2018), shock tube testing, which allows for the simulation of shock waves emanating from far-field blast explosion (i.e., planar shock front) without the need for high explosives, has allowed structural elements, connections, and sub-assemblies to be investigated whilst obtaining relatively high amounts of quantitative results, such as reactions, deformations, and deflected shapes. This includes studies on light-frame construction (e.g., Lacroix and Doudak, 2015; Viau and Doudak, 2016a; 2016b; 2017), glued-laminated (glulam) timber elements (e.g., Lacroix and Doudak, 2018a), and cross-laminated timber (CLT) panels (e.g., Poulin et al., 2018).

4. Code implications for blast design

Both Canada and the United States have in recent decades developed initial editions of their respective blast design standards. The Canadian Blast Standard, CSA S850 (2012), provides guidelines and information with required performance criteria for buildings to resist blast loads, in addition to explosion types, blast wave, materials strength under blast loads, and guidance on design for steel, concrete, masonry, and wood components. There are four response limits for wooden element based on the type and are mainly based on elements ductility. In all the aforementioned shock tube studies, HSR effects were quantified through dynamic increase factors (DIF), which may be used by designers when designing these elements to resist blast explosions. Based on a review of the available experimental test data in tandem, the current versions of the American and Canadian blast codes assign a DIF value of 1.4 to all wood element types. While this value has been corroborated for solid sawn lumber products by several research studies, it has been found not to be applicable to other types of engineered wood products, such as glulam and CLT (Doudak et al., 2022).

WG3.SG3.02

Progressive and disproportionate collapse of wooden structures under blast effects

Alicja C. Przystup, University of Edinburgh (UK); **Abla Krouma**, University of Ottawa (Canada); **Johannes A. J. Huber**, Luleå University of Technology (Sweden); **Christian Viau**, Carleton University (Canada)

1. Introduction

Starossek (2007) defines progressive collapse (PC) as one characterised by the disproportion between the triggering event and the resulting damage. Because of this, progressive and disproportionate collapse (DC) are often used interchangeably, however other sources distinguish these two phenomena (ARUP, 2011). PC happens when a chain of events occurs after the initial damage is directly caused by one another, and therefore the term characterises the type of collapse behaviour. DC on the other hand characterises the proportionality of the result to the initial damage, which can be arbitrarily defined. Therefore, a collapse event can in fact be either, both, and neither, however they often occur concurrently. The progressive and disproportionate collapse prevention includes non-structural protective measures (minimising probability of exposure to triggering event), reducing the risk of initial damage after the triggering event (key element design, overdesign), and designing for structural robustness. Robustness is defined by Starossek and Haberland (2012) as the ability of the structure to withstand the abnormal events without them resulting in disproportionate response. The topic of robustness in timber is investigated in more detail in the WG1. In progressive collapse research, usually an event-independent approach is taken, i.e., the specific exposure causes an initial damage is disregarded (Huber et al., 2018). In contrast, investigating the potential for progressive collapse after exposure to a blast explosion, requires an event-dependent approach.

2. Current standards and regulations

Progressive and disproportionate collapse prevention is directly addressed in Eurocode 1 Part 1-7 (CEN, 2006). The design approach there is divided between two groups of strategies:

1. Identifying the accidental actions and minimising the risk of damage through overdesigning the entire structure or reducing the risk of and vulnerability to the triggering event.
2. Assuming event independent localised damage and introduces alternative load paths, key element design and prescriptive rules for robustness such as ductility and integrity, all of which is encapsulated in Annex A.

It's worth noting that with respect to the second category, the only design calculation methods offered are the horizontal and vertical tie force calculations (assumed to provide sufficient redundancy for formation of alternative load paths), as well as key element design. This methodology considers various possible, albeit rare load scenarios, to which critical load-bearing elements may be exposed (Ellingwood, et al., 2007). Key element design is typically the method of last resort, utilized when alternative load path design does not generate a safe overall design of the structure (Cormie, et al., 2009). These elements are expected to be designed using a static-equivalent pressure of 34 kPa applied on either side of the element; a prescriptive requirement that has been derived based on the expected peak loads generated during the event of Ronan Point (ISE, 2010). This approach has been criticized for being simplistic and not appropriate for most design scenarios. No guidance on element design and dynamic analysis is provided, particularly in terms of high strain-rate effects, charge determination, and modelling methodologies. The code is written as material independent, approaching all buildings. With respect to large timber buildings, there are several issues with applying the current design guidance. Since the modern design codes are written based on reliability theory (Starossek, 2018), these actions and resistances have been based on statistically determined empirical data. This is clearly a problem when pushing the so-far-known limits of a material, as there is no reason to believe that the models developed previously will be appropriate.

3. State-of-the-art

Sørensen (2011) found that particular attention should be given to shear strength due to the brittle behaviour of timber in order to minimize the risk associated with progressive collapse in timber structures. Another consideration was ensuring that connections and main elements had sufficient ductility and strength in addition to ties consideration in the main principal directions. Furthermore, primary and secondary elements' ability to withstand reversal in load direction was identified as a key requirement for structural robustness.

The overwhelming majority of the reviewed literature has concluded that the effectiveness of prescriptive design methods is mostly unknown and overdesigning key elements should be avoided in lieu of performance-based approaches (Mpidi Bita et al., 2022). 127 structural collapse cases of Scandinavian timber buildings were investigated and 84% of the analysed structures were large-span timber structures, with instability being the most common failure mechanism (Frühwald et al.,2007; 2011). In the case of large span structures, increasing the redundancy and ties between elements could be detrimental to the stability of the system and can therefore be the direct cause of the progressive collapse (Starossek, 2006). Additionally, ensuring that connections and main elements have sufficient ductility and strength in addition to ties consideration in the main principal directions. While Alternative Load Path Analyses (ALPAs) have been conducted numerically, e.g. for a bay of a 6-storey CLT building in Huber (2021), a nine-storey mass timber building in Mpidi Bita and Tannert (2019), and a CLT floor system in Huber (2021), no literature on scenario-dependent ALPAs for blast exposures on multi-storey timber buildings is currently available.

A numerical study of a glulam frame was conducted using a non-linear dynamic analysis in the case of middle and edge column removal, however, the nonlinearity that came from materials and imperfections were not considered. The numerical analysis was conducted in three steps. The dynamic amplification factor value was between 1.9 to 2, which could be used in design verifications in linear elastic analysis case. Damping ratio and connection stiffness affected the value, while member stiffness had negligible impact (Cao et al., 2021).

WG3.SG3.03

Behaviour of timber connections under blast loading

Thomas Reynolds, University of Edinburgh (UK**); Christian Viau**, Carleton University (Canada); **Ghasan Doudak**, University of Ottawa (Canada)

1. Introduction

Connections in timber structures, in contrast to steel and reinforced concrete, often have less strength and are generally more flexible than the members to which they connect. As a result, they are the focus of a vast body of research involving dynamic loading, such as seismic and blast. As timber is used for larger and taller public buildings, this area of research will become increasingly important to ensure public safety by limiting the effects of blast explosions. A wide variety of connection types in timber structures currently exists, including dowel-type connections include nails, screws, bolts and dowels, which are arguably most common way to create connections between timber elements on a construction site. Many different types of connections rely on dowel action, where a connector (usually steel) acts across a shear plane to hold two parts together. Examples include slotted-in steel plates with bolts or dowels passing through the timber and the plate (Dorn, de Borst and Eberhardsteiner, 2013; Reynolds et al., 2022), timber-to-timber connections where the connector passes through overlapping timber elements and steel hold-downs or angle-brackets which are secured to the timber with nails or screws (Ringhofer, Brandner and Blaß, 2018). Dowel-type connectors are also used to connect pieces of solid wood to create larger building elements, such as in nail-laminated (Hasan et al., 2019) or dowel-laminated timber (Bouhala et al., 2020; Sotayo et al., 2020). Specialist connection types seek to achieve particular elements of building performance. Connectors for seismic resistance take advantage of friction or yielding of a ductile “fuse” to dissipate energy in a connection and reduce the seismic load on the structure. As connections within between timber elements involve material behaviour in various orthogonal directions, strain-rate effects are expected to occur within these localized regions, however, their extent and magnitude has not been well documented, particularly for blast load.

2. Behaviour of timber connections under high strain rates

Various material properties of timber are strain-rate dependent, and as a result, connections exhibit strain-rate variations of strength and stiffness. “Medium” strain rates, as defined by Cheng et al. (2022), are possible in conventional hydraulic materials testing machines, but high strain rate loading representative of blast require a specialist setup such as a shock tube (McGrath and Doudak, 2021). Disproportionate collapse scenarios may see HSR effects, but there is no clear consensus on the appropriate loading rate for these experimental test programs (Mpidi Bita and Tannert, 2020). Early research on nailed timber joints involving medium strain rates showed strengths approximately 30% higher at a high rate of loading than quasi-static (Girhammar and Andersson, 1988). Various increase in strength and stiffness were found, however, it was noted by the authors that these increases were greatly affected by the slenderness ratio of the nailed joint. In a similar study, monotonic loading of bolted timber joints at two different loading rates, a slow rate (0.042 mm/sec) and a fast rate (25 mm/sec), in both parallel- and perpendicular-to-grain directions, were conducted (Daneff, 1997). The joints in question consisted of two-member wood single-bolt joints. The author concluded that connections exposed to a fast rate of loading exhibit stiffer behaviour and attained higher yield loads than those exposed to a slow rate of loading (Daneff, 1997), however, it was noted that these increases were heavily affected by the slenderness ratio of the connection as well as the direction of loading (parallel versus. perpendicular to grain).

3. Design of connections against blast loading

Sufficient connection ductility and strength under high strain rate loading is required for a timber system to resist blast loads. As in the case of connections for seismic resistance, the strategy when it comes to connection of timber assemblies under blast load is to concentrate the irreversible deformation in ductile connectors, such that damage to the load-bearing timber element is mitigated. Recent work has focused on common types of connections for light-frame wood stud walls. Viau and Doudak (2016a) investigated typical prescriptive code guidelines for light-frame wood stud walls and concluded that the typical nailed connections, including those designed for high seismic regions, did not allow the studs to develop their full flexural capacity due to a premature failure, and thus resulting in hazardous debris. While significant damage in the joist hanger connections was observed, the studs were able to attain their ultimate flexural resistance. It was concluded that overdesigning the connections based on the stud capacity may not be adequate and that proper understanding of the failure mechanism of the connection must be investigated. In regard to mass- and heavy-timber, bolted connections in glulam assemblies (McGrath and Doudak, 2021; Viau and Doudak, 2021b), as well as self-tapping screws and angle bracket connections used in CLT construction (Côté and Doudak, 2019; Viau and Doudak, 2019) were investigate through small- and full-scale testing were conducted through the use of a shock tube.

While evidence of HSR effects has been found in wood connections, further research is required in order to further refine blast design codes in regard to wood connections. Properly detailed connections as well as those designed to fail via ductile mechanism (i.e., wood crushing, yielding of steel) allowed the timber assemblies to withstand larger blast loads when compared to overdesigned connections (Côté and Doudak, 2019; Viau and Doudak, 2019; 2021b). As in the case of connections for seismic resistance, the strategy is to concentrate the irreversible deformation in ductile connectors, so that the relatively brittle timber material is left undamaged. This concept has been applied in isolation (Wang et al., 2017), within precast concrete assemblies subjected to blast loads (Lavarnway and Pollino, 2015), and within glulam and CLT assemblies subjected to blast loads (Viau and Doudak, 2021c). In the latter, energy-absorbing connections (EAC) were designed to ensure that yielding in the EAC always occurred prior to failure of the wood element through capacity-based design. From experimental testing, the implementation of these connections allowed for upwards to twice the amount of blast impulse imparted prior to damage occurring in the wood element, when compared to overdesigned end connections.

WG3.SG3.04

Modelling of blast-loaded timber elements and assemblies

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1. Introduction

The violent transient nature of blast scenarios poses a challenge for building accurate and reliable numerical models of the effects on structures after explosions. The literature concerning modelling of this phenomenon is mainly treating reinforced concrete and structural steel systems. Given the relatively recent trend of building multi-storey timber buildings, investigations regarding wood are scarce when compared to other materials. This report attempts to review of the state of the art concerning modelling considerations of timber structures with regard to blast exposures. In general, numerical models for blast include models based on the Finite Element Method (FEM) and simplifications such as Single Degree of Freedom (SDOF) and Two Degree of Freedom (TDOF) models. As live explosion testing tends to be logistically difficult and expensive, being able to generate and validate numerical models tends to be the preferred approach to study these relatively novel structures under high magnitude, short duration blast loads.

2. Finite element modelling of blast scenarios

The main challenge in conducting finite element modelling regarding effects of a detonation on a structure is that two coupled phenomena need to be considered; i) the explosion's rapid compression of its surrounding fluid (air) with its subsequent pressure shock front, and ii) the structure's response to the shock front, which in return affects the propagation of the pressure wave. Numerical models may often investigate these phenomena in two separate types of models; the blast loads are predicted by models based on Computational Fluid Mechanics (CFD), and the effects on the structure given the loads are predicted by models based on Computational Solid Mechanics (CSM) (Ngo et al., 2007). These uncoupled models usually overestimate the loads, since the structure is assumed to be rigid in the CFD model, whereas in *coupled models,* both phenomena are accounted for simultaneously. The latter tends to provide more accurate results, but is computationally more expensive. In lieu of CFD, the approximate pressure-time history for a given charge weight and standoff distance on a component can be modelled by a triangular-shaped (see Figure 1). These curves can be obtained from what is referred to as the Kingery-Bulmash Blast Parameters, which were empirically derived from explosion testing in free-air (Kingery and Bulmash, 1984).

Finite element models for blast analysis can be made in several commercial software packages, examples include AUTODYN, DYNA3D, LS-DYNA, ABAQUS (Ngo et al., 2007). LS-Dyna, in particular, has extensive documentation on a Wood material model, including strain rate effects, hardening, softening (damage modelling), temperature, moisture content, and user-defined material parameters. ABAQUS does not include specific constitutive laws for wood materials by default, however, this modelling environment can facilitate the analysis of damaged configurations based on inclusion of orthotropy, strain rate effects, hardening, and damage laws that should be properly calibrated.

In numerical models, including simplified models (SDOF and TDOF) and FEM, time needs to be discretised into finite timesteps. For transient problems like blasts, a response history analysis is performed, i.e., the equations of motion governing a system are solved by *direct integration* along these timesteps (Cook et al., 2002). Direct integration can be performed by *explicit or implicit* algorithms. For explicit integration, the state of the system at a subsequent time step is simply extrapolated using only information from the state of the system at its previous time step, which makes each step computationally cheap. For implicit integration, the state of the system at the subsequent time step is calculated accounting for both the state of the previous *and* the subsequent step, which usually involves a Newton-Raphson solution scheme including the computationally expensive conversion of the stiffness matrix. Refer to Huber (2021) for more explanation.

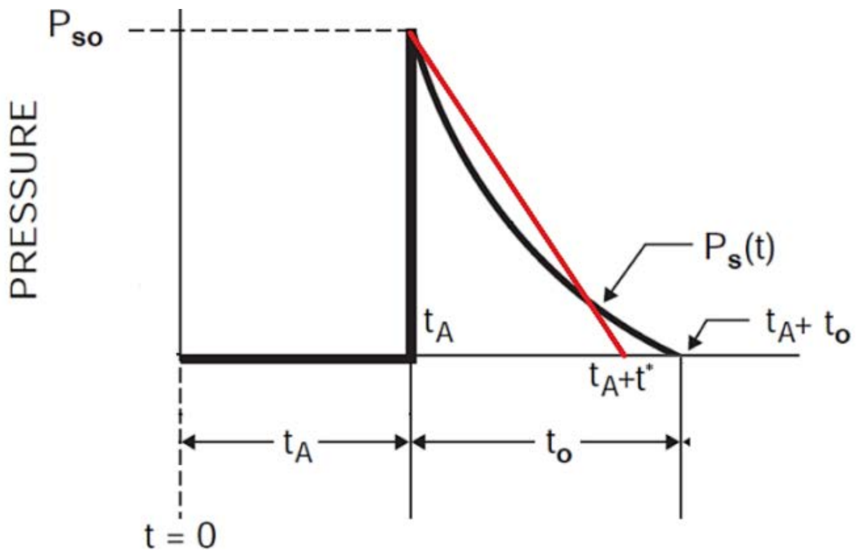

Figure 1: Triangular-shaped curve to model a blast load (adapted from Dusenberry, 2010)

3. Simplified modelling of timber structures subjected to blast

Due to the many uncertainties associated with materials and blast wave characteristics, most of the modelling conducted on wood structures subjected to blast loads has been limited to simplified modelling such as Single-Degree-of-Freedom (SDOF) and Two-Degree-of-Freedom (TDOF) modelling. These approaches consist of idealizing the actual structural element and/or assembly into lumped-mass systems. The use of the former has been proving capable at modelling wood studs (Jacques et al., 2014), stud walls (Lacroix and Doudak, 2015), glulam beams and columns (Lacroix and Doudak, 2018a; 2018b), and CLT panels (Poulin et al., 2018) under blast loads, whereas the latter has been used and validated against experimental full-scale test data for light-frame stud wall with nailed connections (Viau and Doudak, 2016), glulam elements with bolted connections (Viau and Doudak, 2021b), CLT assemblies with self-tapping screws and bearing angles (Côté and Doudak, 2019; Viau and Doudak, 2019), and energy dissipating connections (Viau and Doudak, 2021c) under simulated blast loading (Viau and Doudak 2021a).

WG3.SG3.05

Comments and Questions COST Action Helen Meeting Gothenburg

This chapter lists the questions asked and comments given during the COST Action Helen meeting in Gothenburgh on the 4th and 5th of October 2022.

1. Questions

There isn't any specific Code for blast design on timber buildings in Europe, is it?

What design methodology would (in general) prefer for designing TTBs against blast - robustness or dedicated connections?

Can the connections for blast robustness maybe also be used and beneficial with respect to low damage seismicity, adaptability, repairability aspects etc?

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COST Action CA20139
Holistic design of taller timber buildings (HELEN)

Sustainability and Durability of Taller Timber Buildings: A State-of-the-Art Report

Edited by

Steffen Franke

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IMPRESSUM

Sustainability and Durability of Taller Timber Buildings: A State-of-the-Art Report

Working Group 4, COST Action CA20139 - Holistic Design of Taller Timber Buildings - HELEN

Working Group 4 Leader: Steffen Franke

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Foreword

A holistic designs approach can make taller timber buildings even more sustainable compared to conventional buildings made mainly of steel, concrete, or masonry. Durability is meant in terms of moisture safety for longevity of timber products, assemblies and structures, and the possibility to increase utility by e.g., reuse or quality cascading in upcoming product life.

Robustness should express the general resistance of timber against moisture within certain limits. To no exceed these limits a proper moisture management is necessary and must be considered already in holistic design for taller timber structures, considering the different stage from factory until operation. Robustness also has to do with the resilience of structures and assemblies and their repairability to maintain the majority of moisture affected situations. This robustness concept exercised for entire buildings also enables to additionally lower environmental footprint because it allows to keep buildings in service as long technical possible and avoids. Therefore, many crosslinks with WG1 – Robustness, Reuse and Repair exists.

To benefit from these advantages, tall timber buildings must have a similar or almost equal durability compared to conventional buildings. Otherwise, the sustainability advantages would be compromised. Therefore, tall timber buildings must be designed, considering the special properties of timber as construction material. The goal is to maximize resistance of this type of timber structures and envelope systems against various moisture exposure scenarios causing deterioration and damage. Not only design but also execution of timber structures is of relevance; namely construction site activities and prevention from exposure, further the operation and maintenance of large and tall timber buildings needs a focus on risk reduction measures.

Despite these special requests for the designer, tall timber structures are already built in Europe, but also North America and Australia are competing since a few years. Thus, a lot of research work and development have been done especially in Europe on this field.

The aim of this document is to report the state of the art in terms of research and practice of durability and sustainability of tall timber building systems, in order to summarize the existing knowledge in the single countries and to develop a common understanding of the design for moisture safe and robust execution and operation of tall timber buildings.

This report was made within the framework of WG4-Sustainability and durability within COST Action CA20139 and thus, reflects parts of the work and the discussions within WG4 and will cover the relevant issues, such as given below. It intends to reflect the information and studies available around the world, but especially in Europe through the active contribution and participation of experts from various countries involved in this Action.

- Part 1 Sustainability
- Part 2 Life cycle assessment
- Part 3 Durability in relation to environmental impact and circularity
- Part 4 Moisture impact and management

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Part 1

Sustainability

Sub Group (SG) 1

WG4.SG1.01

Sustainability Assessment of Tall Timber Buildings

Shady Attia, University of Liege (Belgium)

Sustainable construction is riding on cutting-edge technology, and new rapid advancements often come with unique, often confusing, terminology. The following will provide much-needed clarity on several commonly used concepts and terms to help navigate the complex lexicon of the green buildings industry.

1 Introduction

The EU and the United Nations have common goals for a sustainable future. The UN Sustainable Development Goals are a useful vehicle to project the EU's values and objectives globally and provide a shared framework useful for international partnerships. On the other hand, the 'fit for 55' package is part of the European Green Deal, which aims to put the EU firmly on the path toward climate neutrality by 2050. The built environment is one of the key sectors where low-carbon solutions must be implemented because it is, directly and indirectly, responsible for 39% of global carbon emissions. Emissions come from operating existing buildings and from constructing new ones.

With the accelerated transformation towards low-carbon and resource-productive economies, and the continuing interest and desire of designers and consumers to use more environmentally friendly materials, the future for wood and timber products seems particularly positive. Hybrid softwood and hardwood CLT panels are gathering a foothold in different countries worldwide (Woodard & Milner, 2016). In this context, it is essential to ask the following research question:

- How to assess the sustainability of Tall Timber Buildings?

1.1 Tall buildings sustainability: low-rise buildings are the future

High-rise buildings have a drastically higher carbon impact compared to densely built, low-rise environments. Building tall timber buildings means using more materials that must be robust enough to withstand wind loads and earthquakes and resist fire risks. Tall timber buildings require increasingly sophisticated building services and networks besides continuous maintenance (Samyn & Attali, 2014). Moreover, high-rise buildings require intensive investment in security and social cohesion. Perhaps various aspects need to be fine-tuned for tall timber buildings to be considered sustainable solutions for urban planning.

1.2 Material efficiency: Use fewer materials

During the last decade, Europe's attention turned to reducing Greenhouse Gas (GHG) emissions from the built environment through renewable, low-carbon building materials, such as mass timber. Timber is a sustainable and low-carbon construction material that presents itself as a compelling alternative to steel and concrete. Scientific evidence proves that the greatest levels of GHG abatement from biomass currently occur when the wood is used as a construction material… to temporarily store carbon and displace high-carbon cement, brick, and steel.

Material efficiency means producing the same result with reduced amounts or lower grades of raw materials. Therefore, building renovation is the most sustainable practice that Europe should adopt by 2050. The best sustainable act is to avoid new construction and to improve the energy and materials efficiency of existing buildings. Based on the *Trias Ecological* principles (Duijvestein, 2010) and similar to the basic rules of *Trias Energetica* that are used in the design of zero-energy buildings (Attia, 2018), the *Trias Materia* is a set of basic rules that aim to reach zero carbon buildings (first) step here (see Figure 1): 1) prevent demand (avoid building new), and limit use, followed by 2) use renewable raw materials and 3) use natural fossil resources efficiently.

In this context, wood is very effective in replacing carbon-intensive materials such as concrete or steel if sourced from sustainability-managed forests. Wood is lightweight; it weighs 20% of a concrete building. It is a strong building material with excellent insulating properties. The ability of mass timber elements to emit 30% to 40% less greenhouse gas emissions (101 kg CO_2 eq/m^2) than concrete makes it an extremely sustainable material (Liang et al., 2020). Substituting wood for conventional building materials reduces emissions by 60-80% without considering the biogenic carbon or the sequestration capacity (Al-Obaidy et al., 2022; Himes & Busby, 2020).

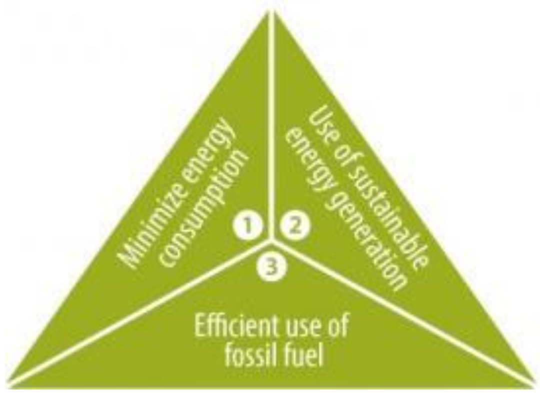

Figure 1a: Trias Energetica (Duijvestein, 2010)

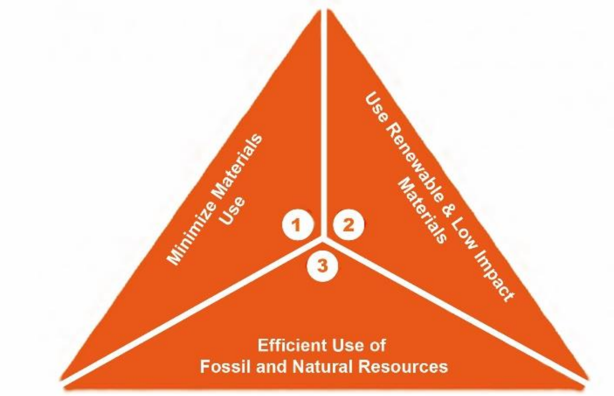

Figure 1a: Trias Materia (Duijvestein, 2010)

2 Terms and Definitions

There are lots of terms that get used in the field of sustainability, and what they all mean can get confusing.

Greenhouse gases A greenhouse gas (or GHG for short) is any gas in the atmosphere which absorbs and re-emits heat and thereby keeps the planet's atmosphere warmer than it otherwise would be. The main GHGs in the Earth's atmosphere are water vapor, carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), and ozone.

Global warming potential The GWP of a GHG indicates the amount of warming a gas causes over a given period (usually 100 years). GWP is an index, with CO_2 having an index value of 1, and the GWP for all other GHGs is the number of times more warming they cause compared to CO2. E.g., 1kg of methane causes 25 times more warming over 100 years compared to 1kg of CO2, so methane has a GWP of 25.

Carbon dioxide CO_2 is the most common GHG emitted by human activities in terms of the quantity released and the total impact on global warming. As a result, the term "CO2" is sometimes used as a shorthand expression for all greenhouse gases. However, this can confuse, and a more accurate way of collectively referring to several GHGs is to use the term "carbon dioxide equivalent" or "CO_{2e}". Because CO_2 is considered the most important greenhouse gas, some GHG assessments or reports only include CO_2, and don't consider the other greenhouse gases, and this can lead to an understatement of the total global warming impact. Greenhouse gas inventories are more complete if they include all GHGs, not just CO_2.

3 Timber and Greenhouse Gas Emissions

Relative to other construction materials used for frame building construction, timber has arguably the best environmental and sustainability credentials, particularly from a life-cycle assessment perspective (Woodard & Milner, 2016). However, The life cycle of a building spans at least three human generations: the first generation planted the tree, the second built the building, and the last one inherited it. Most standards compress these transgenerational processes within one life cycle with immediate benefits and burdens.

Literature suggests that despite the whole life cycle, GHG emission studies in the timber studies construction stage are not given enough due consideration (Sandanayake et al., 2018). The emissions at the construction stage are often critical for designers and contractors who seek to maintain a vibrant construction environment and sustainable construction practices. Therefore is very important to calculate the GHG emissions at the construction stage of timber building. Sensitivity analysis should always be conducted to investigate the different variations of material and transportation usage and compositions.

3.1 GHG emissions and timber

Total GHG emissions can be calculated from the equation below.

$$E_{tot} = \sum_{m,=1}^{n} E_{m,GHG} \tag{1}$$

E_{tot} is the total GHG emissions, and $E_{m,GHG}$ is the GHG emissions from the mth emission source.

3.2 Biogenic Carbon and Timber

The significance of methodological choices related to the assessment of biogenic carbon is expected to increase as future buildings continue to reduce their operational GHG. Two main LCA approaches are used to assess the impact of biogenic carbon uptake and release.

In the first approach, the ‘0/0 approach’ or ‘carbon neutral approach, the release of CO_2 from a bio-based product at the end of its life is balanced by an equivalent uptake of CO_2 during biomass growth. Consequently, there is no consideration of biogenic CO_2 uptake (0) and release (0) (Hoxha et al., 2020).

The second approach, which is referred to as the ‘–1/+1’ approach, consists of tracking all biogenic carbon flows over the building life cycle. In this approach, both biogenic CO_2 uptake (–1) and release (+1) are considered, as well as the transfers of biogenic carbon between the different systems (Hoxha et al., 2020).

The European standards EN 15978, EN 15804, and EPDs follow the cradle-to-gate options, mostly applying the –1/+1 approach. The impacts and carbon-storage credits are not included in most other existing methods. This means timber can not be considered carbon storage or sink. In other words, timber’s sequestration ability is not considered.

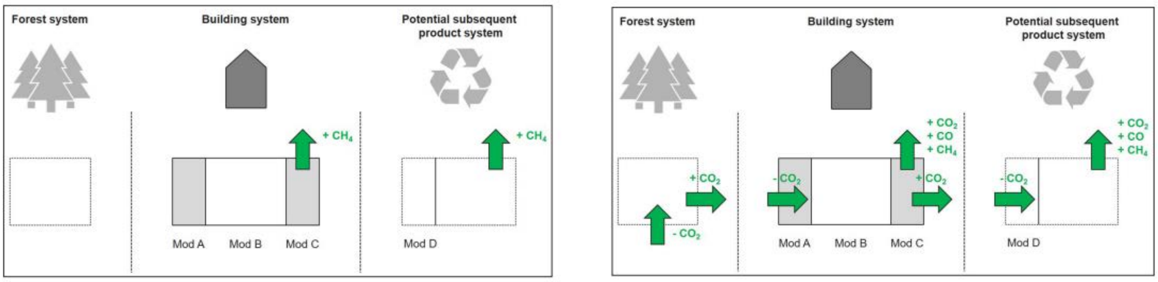

Figure 3a: The 0/0 approach to model biogenic carbon uptake and release. Dotted lines indicate the production systems that fall outside the building system boundaries. Figure 3b: The –1/+1 approach to model biogenic carbon uptake and release. Dotted lines indicate the production systems that fall outside the building system boundaries

3.3 Sustainable Timber Sourcing

Deforestation and forest degradation highlight the high risk of using timber in construction. Sustainable timber requires responsible harvesting from well-managed forests that are continuously replenished and ensure that there is no damage to the surrounding environment or native flora and fauna (Woodard & Milner, 2016). In Europe, forest management certification schemes, including the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC), assure that all wood and wood-based products originate from sustainable sources. However, there is growing evidence that European, Asian, and South American forest loss is driven primarily by clearance for agricultural reasons and by illegal logging. Without the documentation of the chain of custody certification of timber used in construction, that use of timber will be a broken path toward low impact built environment.

There is a need to enhance the viability of timber in tall timber buildings worldwide. Europe must increase its afforestation, reforestation, and sustainable management efforts without competing with agricultural land to meet the demand by consumers for wood-based products. However, it is essential first to stop the clearance for agricultural reasons, illegal logging, and the import of rainforest timber to ensure the sustainable management and use of timber as a renewable resource (Ramage et al., 2017).

WG4.SG1.02

Environmental Impact Assessment of Timber in Construction in Europe

Shady Attia, University of Liege (Belgium)

To investigate the environmental impact of timber in construction and the potential of mitigating the increase in embodied GHG emissions from new tall timber, a life cycle assessment (LCA) needs to be performed. In Europe, legislative and regulatory measures have been taken to effectively increase the carbon efficiency of buildings, thereby reducing GHG emissions. The following report will summarize the EU's main LCA calculation methods and regulatory framework.

1 Introduction

The EU and the United Nations have common goals for a sustainable future. The UN Sustainable Development Goals are a useful vehicle to project the EU's values and objectives globally and provide a shared framework useful for international partnerships. On the other hand, the 'fit for 55' package is part of the European Green Deal, which aims to put the EU firmly on the path toward climate neutrality by 2050. The built environment is one of the key sectors where low-carbon solutions must be implemented because it is, directly and indirectly, responsible for 39% of global carbon emissions. Emissions come from operating existing buildings and from constructing new ones.

2 Environmental Impact Assessment

EN 15978 is a European Standard that specifies the calculation method, based on Life Cycle Assessment (LCA) and other quantified environmental information, to assess the environmental performance of a building and gives the means for the reporting and communication of the outcome of the assessment. The standard applies to new and existing buildings and refurbishment projects (CEN, 2011).

The approach to the assessment covers all stages of the building life cycle following a cradle-to-grave approach. As shown in Figure 02, there are six life cycle stages of buildings: material extraction A1-2, manufacturing A3, transportation A4, construction A5, refurbishment and replacement B4-5, and disposal activities C4 at the end of the building's life. It also includes the impacts of all material lost at every stage. It excludes the 'operational energy' used within the building when it is in use, for example, heating, cooling, lighting, and running appliances.

The route tracing embodied GHG back to the cradle requires a cradle-to-cradle approach, where the Reuse, Recovery, and Recycling potential (D) is considered, as shown in Fig. 2. Including circularity and materials reuse in the sustainability assessment open the door for a large debate to assess the impact of biogenic carbon uptake and release.

2.1 LCA Boundary Conditions

Before any environmental impact assessment of the Tall Timber Building, it is essential to determine the LCA boundary conditions. Determining the goals is very important because it guides the methodological choices. The scoping includes determining the emissions and resources according to their impact categories and selecting the Environmental indicators in LCA.

For example, different functional units can be used in LCA studies for various purposes. The functional unit choice was found to bias the results considerably (de Simone Souza et al., 2021). Measuring the environmental impact of tall timber buildings per square meter of floor area versus kg of timber or cubic meter of timber can create a substantial difference and bias the results. The definition of material quantities is key to avoiding bias and reducing the uncertainty of the results when comparing tall timber buildings' environmental performances.

Moreover, there are three levels of environmental impact assessment regarding Timber Buildings.

1) perform an LCA on the product level. Specific building elements or materials components will be used and tested for evaluation against EN 15804.

2) performance and LCA on the structural level. The evaluation mainly focuses on the load-bearing structure, allowing us to compare and assess different components, compositions, and structural families.

3) perform an LCA on the building level. The whole building is evaluated by considering the structural and envelope elements, including finishing materials and cladding. The evaluation focuses on building hotspot analysis and construction details, which make it more comprehensive and accurate.

Therefore it is crucial to pay attention to the definition of LCA's goal and scope as indicated in ISO 14040 and to find an agreement on the boundary conditions and LCA methodological approach.

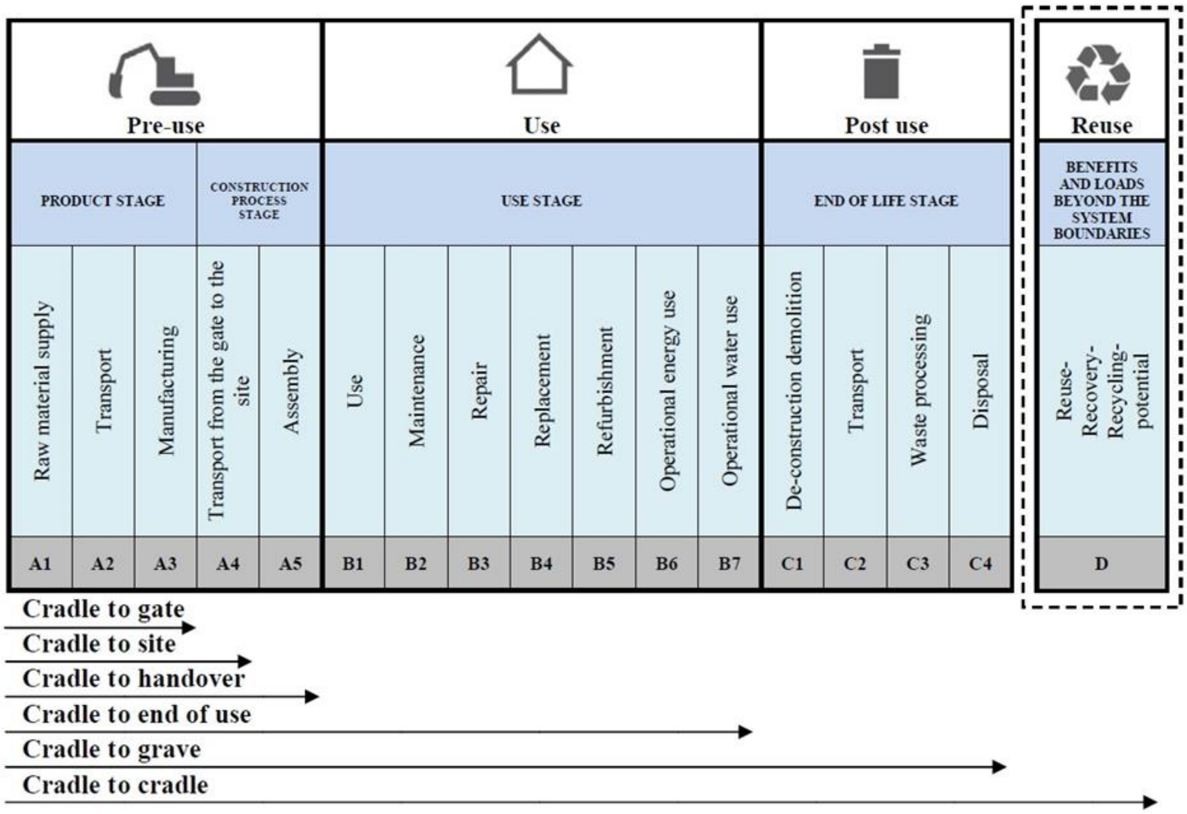

Figure 2: Description of the stages during the buildings' life, according to EN 15978.:2012, p.21

2.2 LCA Indicators

The seven indicators in Table 1. are those specified by European standard EN 15804 and are widely used in LCA and EPD studies worldwide. They can be used as a default core set of indicators, particularly within the construction industry. Each indicator is presented using a common unit (e.g., kg CO_2 equivalent to global warming potential). However, the choice of indicators for a specific study should always be defined as part of its goal and scope phase.

Table 1 Summary of LCA indicators found in EN 15804

Climate change	Ozone Depletion	Eutrophication	Acidification of soil and water	Formation of photo oxidants	Abiotic depletion potential	Primary energy
Global Warming Potential (GWP)	Ozone Depletion Potential (ODP)	Eutrophication Potential (EP)	Acidification Potential (AP)	Photochemical Ozone Creation Potential (POCP)	Abiotic resource depletion - elements (ADPe) / Abiotic resource depletion - fossil fuels (ADPf)	Primary energy renewable total (PERT) / Primary energy non-renewable total (PENRT)
kg CO2-equivalent	kg R11-equivalent	kg PO43-equivalent	kg SO2-equivalent	kg C2H4-equivalent	kg Sb equivalent / MJ	MJ / kWh

3 EU regulatory Framework

The following topics summarize the EU regulatory standards concerning timber sustainability assessment in buildings.

3.1 Construction Product Regulation

The Construction Products Regulation (CPR) lays down harmonized rules for marketing construction products in the EU. The Regulation provides a common technical language to assess the performance of construction products (Wardal & Briard, 2022). It ensures that reliable information is available to professionals, public authorities, and consumers to compare the performance of products from different manufacturers in different countries. CPR basic requirements include the following criteria :

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health, and environment
4. Safety in use and accessibility
5. Protection against noise
6. Energy economy and heat retention
7. Sustainable use of natural resources (EN 15804+A2)

The CPR is the new tool for connecting a product's environmental performance to the EU's evolving building requirements

3.2 EPD

The cornerstone EPD standard, EN 15804, has been broadly adopted worldwide. EN 15804 +A2 was approved and has been mandatory since July 2022. One of the most significant changes in EN 15804+A2 concerns biogenic carbon in all forms. In EN 15804+A1, it was possible to deduce biogenic carbon stored in a product from cradle-to-gate impacts and add them back to represent their release in the end-of-life phase; but only if the product came from sustainably managed forestry. This created some contention within the industry, and EN 15804+A2 resolves these problems.

In EN 15804+A2, the climate impact category is split into four reported categories. The previous single Global Warming Potential category is no longer provided (OneClickLCA, 2022). The new categories are:

- Climate change – total (sum of subcategories)
- Climate change – fossil
- Climate change – biogenic
- Climate change – LULUC (land use and land use changes)

The new standard makes the minimum scope for all products to cover modules A1-A3, C1-C4, and D. This means that products must declare both the cradle-to-gate and end-of-life phases and the external impacts outside the system boundary. Only a few products are exempt.

At the same time, the rules for calculating the benefits for module D after end-of-life is now defined in a significantly more complex manner. The new calculation rules follow the PEF methodology. The calculation rules are provided in Annex D of EN 15804+A2.

3.3 Levels

Level(s) is a new European approach to assess and report on the sustainability performance of buildings throughout the life-cycle of buildings.

3.4 Materials Passport

Material Passports give building materials an 'identity'. The goal of the passports is to generate value by mapping and highlighting the potential for the reuse and recycling of products and materials for varying stakeholders (Hoosain et al., 2021). Additionally, a material passport can provide insight into the health and safety aspects of a material/product. In the EU, different varieties of passports are available, as well as how they can be applied to your project(s) (Gómez-Gil et al., 2022). The European Commission plans to introduce a digital product passport DPP early next year that would contain information about the composition of goods on the European market to help boost their chances of reusing and recycling. The digital product passport under consideration by the European Commission relies heavily on the digital infrastructure and five years of experience of Madaster (https://madaster.com), the "material register", the first online platform that facilitates the generation and central standardized registration of material passports, now active in several European countries such as the Netherlands, Switzerland, Germany, Norway, Belgium, Denmark (Heisel & Rau-Oberhuber, 2020).

WG4.SG1.03

Potential of fast growing hardwoods for taller wood-based buildings

Joris Van Acker, Ghent University (Belgium)

1 Introduction

The interest in new green building products has increased substantially over the last decades. There is extra emphasis on the utilization of hardwoods linked to the increased role of broadleaved tree species in forestry. This consistently increased focus on green development is mainly due to the public concern of the impact of global warming. There are quite some companies, institutes and authorities that have started making efforts on sustainable timber buildings. Glue laminated timber (GLT, glulam) and the introduction of cross laminated timber (CLT) are now established engineered wood products (EWPs) and are critical assets in timber building constructions. These products are mainly based on softwoods, however hardwood species could be key to further innovations. There are critical advantages in using hardwoods in the construction sector, especially when considering production output efficiency and sustainability. Firstly, there are opportunities in increasing the use of common hardwood products like plywood by means of focussing on construction end use. Secondly, other more specific structural engineered wood products like veneer and strand based LVL, LSL and I-joists should be regarded as additional tools to incorporate more hardwoods in construction alongside the massive timber options based on CLT and glulam. Especially, the role of fast-growing species like hybrid poplar clones are of interest as these are very suitable to link with production in relation to plantations and agroforestry.

2 Hardwood as resource

2.1 Trends

Hardwood forests are Europe's largest overlooked renewable resource. Broadleaved tree species account for 43% or 15.0 billion m3 of the European growing stock in forests. Hardwoods present the natural forest ecosystems in the largest part of Europe. Historically, hardwoods were widely used in construction, furniture, flooring, commodities, paper etc. Nowadays however, the forest-based industries in Europe are predominately based on softwood use. The largest share of hardwood today is mainly used inefficiently for energy generation. To valorise better the rich hardwood resource of Europe, it is essential to connect the forestry chain with the transforming industries and the final customers. Hardwoods represent the primary opportunity to foster a long-term strategic pathway for sustainable development of the emerging forest-based circular bio-economy and thus respond to major key societal and environmental global challenges (von Lengefeld and Kies 2018).

2.2 Hybrid poplar

During last century, fast-growing poplar clones have mainly been selected with a focus on specific end uses like the production of matches, plywood or pulp-based products. Today, a lot of new poplar and also willow clones are intended for short rotation coppice, and criteria for selection have been in part adjusted. The wood resource obtained from the fast-growing tree species is considered important to enable a higher production in the future and hence selection and breeding of these deciduous trees has been a major part of sylvicultural and even agricultural frameworks. Furthermore, in many ways, poplar trees can be considered to be the best potential alternative to softwood species for engineered wood products (Van Acker et al. 2016). The applications related to biomass for energy and other less tree quality dependent end uses should be part of an integrated approach.

Mainly hybrid poplar is used in man-made plantations and agroforestry worldwide. The high environmental adaptability, high growth rate and short rotation period (often less than 20 years) make poplar one of the most efficient tree species in terms of sustainability. The development of engineered construction products based on poplar wood fits within the larger strategies to use more hardwoods for construction. The use of wood from fast-growing plantations contributes to enhance their important role for economy, society and environment, which is linked to a sustainable management and processing. The construction sector is essential to maximize this potential by creating added value to the whole chain through high performing EWPs.

3 Hardwood Engineered Wood Products

3.1 Trends

Most engineered components in North America are manufactured from softwoods, such as Douglas-fir, the southern pines, or spruce–pine–fir lumber (Ross and Shmulsky 2021). However, significant research and development efforts have been devoted toward investigating the use of lower grade hardwood resources in engineered materials and components.

The main issues with using hardwoods for CLT production, compared to softwood operations, are quick dulling of cutting tools because of higher hardwood density and a longer pressing time (Adhikari et al. 2020). Other factors, such as moisture content, various dimensions of the lumber, and the caustic nature of some species, were highlighted as limitations for the use of hardwood lumber in CLT panels. The primary concern of the manufacturers was the availability of hardwood lumber in the required quality and quantity.

Although virtually all CLT structures are manufactured using softwood species, there is growing interest in the possibility of manufacturing CLT panels out of hardwoods in North America. Research on hardwood CLT is scarce but existing results suggest that it is technically feasible (Espinoza and Buehlmann 2018). Crovella et al. (2019) compared the mechanical properties of lower grade softwood and hardwood CLT panels. Because of their availability, mechanical properties and distinctive appearance, there is a growing interest for the use of hardwood species in structural products such as glued-laminated timber. Based on assessing bonding and structural grading of northern hardwoods white ash (*Fraxinus americana* L.), yellow birch (*Betula alleghaniensis* Britt.) and white oak (*Quercus alba* L.) are considered promising species for the manufacture of Canadian hardwood glulam (Morin-Bernard et al. 2021).

Aicher et al. (2018) reported on hardwood glulam (GLT) beams produced industrially from European hardwoods like oak, beech, sweet chestnut and ash as well as the tropical species as teak, keruing, melangangai and light red meranti.

Gilbert et al. (2018) reported on mechanical properties perpendicular to the grain and in shear of glued rotary peeled veneers, as would be encountered in veneer-based structural products, of three species recovered from juvenile (early to mid-rotation) subtropical hardwood plantation logs. This allowed to perform a reliability analysis of Laminated Veneer Lumber (LVL) beams manufactured (Gilbert et al. 2019). Shukla and Kamdem (2008) investigated the properties of laminated veneer lumber (LVL) made with low density hardwood species using cross-linked polyvinyl acetate (PVAc) adhesive and thin veneers of silver maple, yellow poplar and aspen.

3.2 Glulam and CLT based on poplar

Due to its average mechanical properties, poplar, a fast-growing species, has been disfavored compared to stronger species for several decades. Glued laminated timber (GLT) beams made with this species revealed a very promising mechanical behaviour as bending strength tests evidenced a ductile behavior on more than 70% of the beams (Monteiro et al. 2020). Poplar was considered due to the increase of availability in Portuguese forest and its relative low density combined with good mechanical properties (Martins et al. 2017).

Wang et al. (2018) indicated that the rolling shear properties increase with distance to the pith when using fast growing poplar wood as the cross-layers in CLT. With the expansion of CLT material throughout the global construction community, an effort is being made to explore the use of regionally produced CLT materials from Iran, including the testing of fast-grown poplar (*Populus alba*) (Hematabadi et al. 2020).

3.3 Laminated Veneer Lumber

Knorz and Van de Kuilen (2012) made a high-capacity engineered wood product-LVL of European Beech (*Fagus sylvatica* L.), named BauBuche, which is a laminated veneer lumber made from locally sourced beech manufactured exclusively by Pollmeier. Aspen (*Populus tremuloides*) is a relatively new substitute species in North America for LVL production. It is worthy to note that two LVL mills in Canada pioneered the manufacture of aspen LVL. The success of these mills demonstrate that poplars are very suitable for LVL production. A novel laminated veneer lumber (LVL) was produced with poplar fibrosis veneers and phenolic formaldehyde. Tests were conducted to evaluate the properties of this product with different densities (ranging from 0.8 to 1.2 g cm^{-3}). The mechanical properties and water resistance were observed to be superior to those values of the traditional LVL (Wei et al. 2019).

3.4 Modified hardwood EWPs

The concept of service life prediction (SLP) is of major importance for the utilisation of wood and wood products. Glulam beams, which were made from hydrothermally treated poplar (*Populus deltoides*) showed that the hydrothermal treatment reduced the cross-sectional moisture induced stresses as well as relevant moisture gradients and it also caused an increase of the bending strength as well as stiffness of the treated wood and the glulam beams (Mirzaei et al. 2017). Van Acker et al. (2020) presented some innovative approaches to increase service life of poplar lightweight hardwood construction products (Table 1).

4 Conclusions

While there is still a strong reliance on softwood production, there is a clear need to involve also hardwoods in the value chain for building with timber. In this context, fast growing hardwood plantations have a strong potential to furthermore increase and complement the regional production of forests, especially in view of an increasing demand for wood raw materials in the emerging bio-economy, limiting raw wood materials transportation. EWPs can be produced using fit-for-purpose processing for building with wood complying with requirements on performance related to durability (service life), fire safety, earthquake resistance, high-rise and low energy construction, among others. EWPs will contribute to the main advantages of building with wood: (1) Fast: short building time, often 30% faster, (2) Light: very good strength to stiffness ratio, and (3) Green: sustainable especially when using bioenergy. This makes EWP increasingly important for contemporary construction and renovation of buildings and infrastructures. EWPs based on sawn wood like Glulam or GLT (Glued Laminated Timber), CLT (Cross Laminated Timber), veneer based panels and beams

Table 1: Options to increase service life of Engineered Wood Products (EWP).

Component	EWP	Durable wood	Vacuum pressure[1]	Glue-line additive	Surface spray[2]	Thermal modification	Chemical modification	Resin[3]	Coatings
Strand	OSB	-	-	±	+	+	+	+	-
	LSL	-	-	±	±	-	-	+	-
Veneer	Plywood	+	+	+	+	+	±	+	+
	LVL	±	±	+	±	±	±	+	+
Timber	CLT	+	+	-	+	+	±	±	+
	GLT	+	+	-	±	±	±	±	+

Legend: +: existing option, ±: feasible option, -: less probable option

1: deep impregnation with biocides; 2: surface biocide application with potential diffusion, e.g. borates, 3: analogue to glue used for production or a hydrophobing agent; Abbreviations: EWP = engineered wood product; OSB = oriented strand board; LSL = laminated strand lumber; LVL = laminated veneer lumber; CLT = cross laminated timber; GLT = glue laminated timber or glulam.

like plywood or LVL (Laminated Veneered Lumber) and strand based products OSB (Oriented Strand Board), LSL (Laminated Strand Lumber) and the similar OSL (Oriented Strand Lumber) and derived I-joists are ready for a large-scale use in structural and functional applications - for massive timber constructions, prefabricated thermally insulated walls and timber frame structures, respectively - on full compliance with current standards and rules.

A larger use of hardwoods in the building sector will underpin sustainability and environmental objectives related to greenhouse gas emission and significantly contribute to the circular economy in particular through the improvement of a better vertical integration between cultivation and wood industry as part of the future bio economy. The latter is particularly interesting for rural communities in low wood production countries.

Engineered wood products (EWPs) for high-valued building applications, both for new structures and renovation, can contribute to implement a new generation of zero waste - positive environmental impact building systems based on products specially designed in order to optimize mechanical performance, thermal insulation, service life and seismic behavior. In this framework, the wood resource derived from (fast growing) hardwood species and transformed in EWPs fit-for-purpose materials are able to cover multi-story buildings and go beyond 25 m span structures, addressing the demand for new and sustainable construction products, which meet the challenges of modern society concerning performance and sustainability. The above raw material can provide complementary products to the softwood-based ones with a clear link to local home-grown timber production with very high growth rate.

Part 2

Life Cycle Assessment

Sub Group (SG) 2

WG4.SG2.01

LCA of wood-based structures for taller timber buildings

Rafael Novais Passarelli, UHasselt (Belgium)

1 Introduction

This study develops a literature review of all papers published in the Journal of Building and Environment from January 1st, 2000, to July 31st, 2022, on the LCA (Lifecycle Assessment) of taller timber buildings. By studying the body of knowledge in this field in the past two decades, the study aims to shed light on its evolutional path, past and current trends, and, most importantly, open scientific gaps to tackle in future research.

2 Method

Using the ScienceDirect database, I performed two searches for papers published in the Building and Environment since 2000 that included all three following terms: 1) LCA, Wood, Construction; or 2) LCA, Timber, Construction. The searches yielded 166 and 102 results, respectively. Search terms were intentionally broad to deliver the highest number of hits possible. Then, an automatic check for duplicates excluded 77 entries, leaving 191 papers denominated as the initial collection (IC). The IC was manually inspected for compliance with the topic, using the following questions: 1) Does the paper develop an LCA study of wood-based construction systems or elements? 2) Do the wood-based construction systems/elements fulfill a structural role in the case study? 3) Is the structural role of the construction system or element in the case study applicable to taller timber buildings with four or more stories? The order of inspection was the following: 1) Title; 2) Keywords; 3) Abstract; 4) Full manuscript (only when needed). If one of the questions above had a negative answer, the paper failed the compliance inspection. Conversely, if all three questions were positive, the paper passed the compliance inspection and became part of the final collection (FC). At the end of the compliance check, 26 entries from the initial collection answered positively to all three questions and constituted the FC. Finally, the FC papers were thoroughly analyzed, with their aims and conclusions summarized in Annex 1.

3 Results and Discussion

Despite taller timber buildings with four or more stories being a reality for more than two decades, there was a surprisingly low number of publications about their LCA in the Journal of Building and Environment, with the vast majority of entries dating from the last couple of years. The count of papers by year (Figure 1) indicates the number of publications on the topic was relatively constant between one and two from 2009 to 2020. In 2021, however, there was a sharp increase in publications with nine published papers. Likewise, the year 2022 already portrays five entries until July. This result suggests a sudden interest in the field by the researchers and the journal. Further analysis of the number of publications by the geographical scope of the study (Figure 2) shows a predominance of Central European countries (9 entries), followed by Canada (5 entries), which most likely coincides with the incidence of mid-to-high-rise timber buildings. Hence, one hypothesis is that the concentration of taller timber buildings in a few countries around the globe contributes to limiting the relevance and interest in LCA studies about these buildings, thus leading to a still small number of papers.

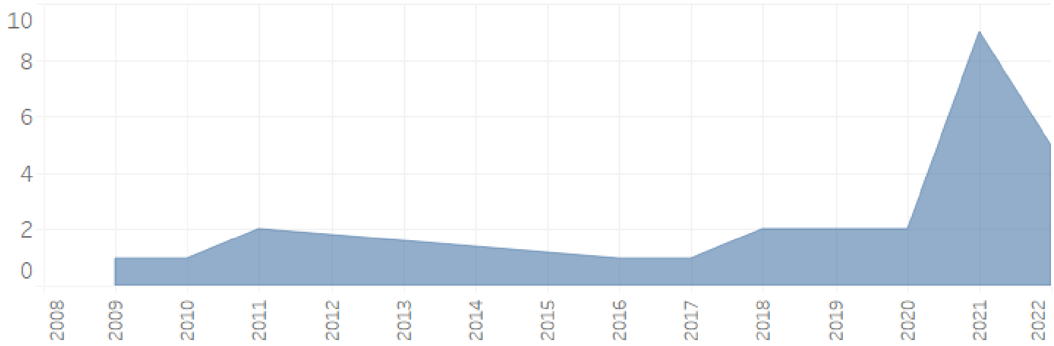

Figure 1: Count of publications by year

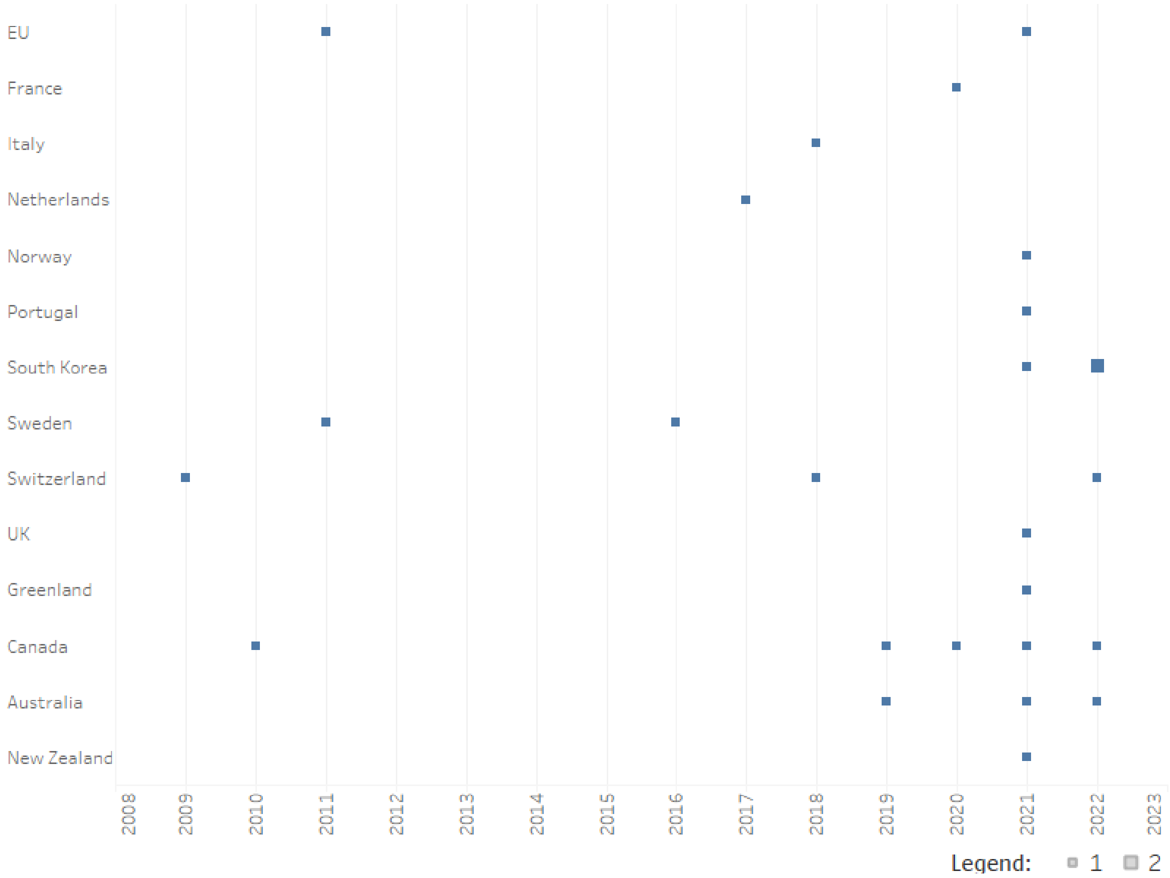

Figure 2: Count of publications by country, by year

The thorough analyses of papers showed that studies from 2010 to 2020 focused on material selection and its evaluation of the environmental impacts of construction. Many publications from this period compared some types of wood-based systems with their equivalent in concrete or steel (Bribián, 2011) (Wallhagen, 2011) (de Klijn-Chevalerias, 2017) (Invidiata, 2018) (Li, 2019). Another set of papers from the same period aimed at discussing the possibilities and shortcomings of the LCA methodology (Kellenberger, 2009) (Sinha, 2016) (Rezaei, 2019). The main goals were to develop more reliable methods and simplified tools to support decision-making during the design and construction processes.

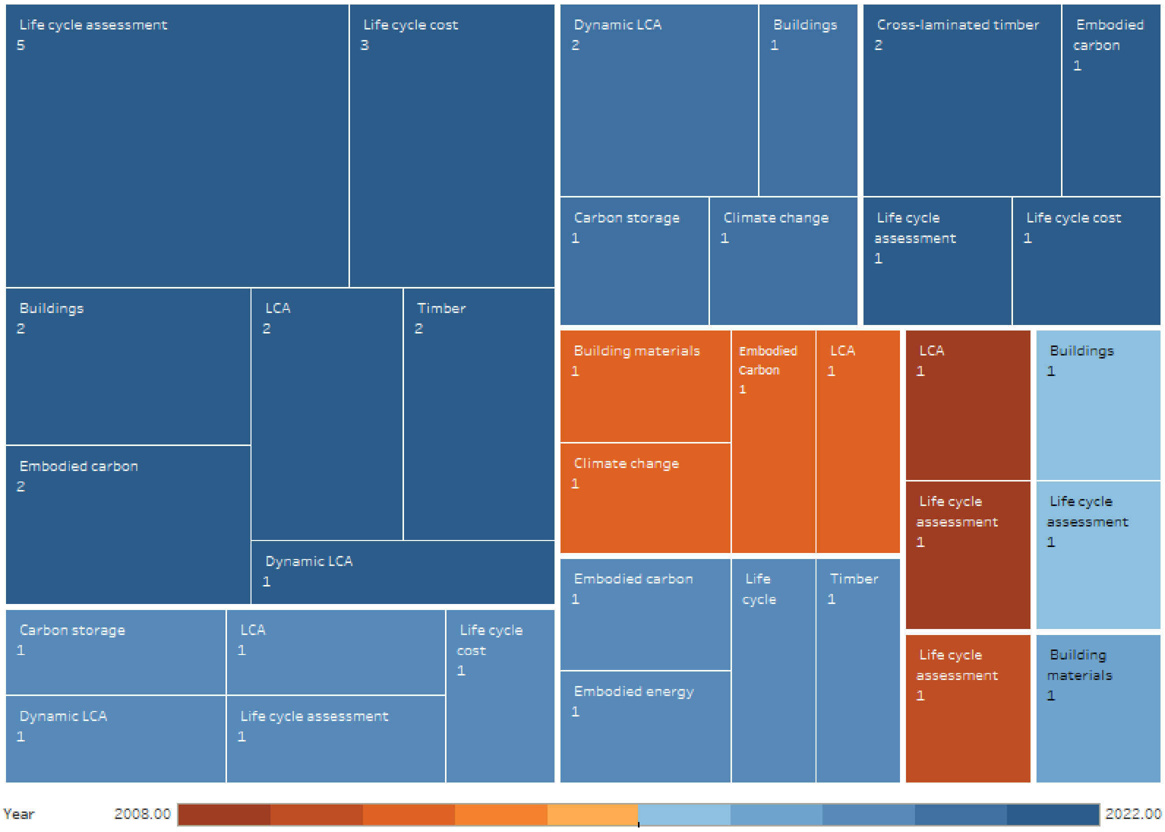

Figure 3: Publication keywords with total incidence > 1, by year.

Nonetheless, a new trend stands out in the transition from the 2010s to the 2020s. Figure 3 displays keywords with more than one hit and indicate an increased interest in the past couple of years in studies involving analyses of carbon storage through a dynamic LCA method. Hence, a considerable number of more recent studies on the LCA of taller timber buildings also started to tackle the time dimension and its influence on environmental performance (Pittau, 2018) (Head, 2020) (Zieger, 2020) (Morris, 2021) (Resch, 2021) (Göswein, 2021) (Robati, 2022). The dynamic LCA studies quantify the extended effects of biogenic carbon storage in fiber-based materials aiming for more accurate assessments of its impacts on buildings and materials. Those studies conclude that considering an expanded time horizon, sometimes up to 500 years (Zieger, 2020), is beneficial to fiber-based products (Zieger, 2020) (Resch, 2021). The results also show that when the timing is considered, the faster the growth rate of fiber-based materials, the more beneficial it is in the short term, which gives an advantage to straw, hemp, and cork over wood (Pittau, 2018), although the differences between fast- and slow-growing biomaterials level out in the long-term (200 years horizon) (Göswein, 2021). In the same line, recent papers started to stress the relevance of the end-of-life scenario and further potential for mitigation of extending the lifespan of buildings and materials through strategies such as design for adaptability, disassembly, and reuse to increase the time-related benefits of wood-based materials (Morris, 2021) (Resch, 2021) (Kröhnert, 2022) (Robati, 2002).

4 Conclusions

This study developed a literature review on the LCA (Lifecycle Assessment) of taller timber buildings from 26 papers published in the Journal of Building and Environment from 2000 to 2022 (July). Therefore, because all results and conclusions refer to only one journal, caution is required when generalizing them to the whole field. The results are, however, useful as an indication of general trends as they relate to one of the most relevant publications in the domain of sustainable construction.

This review study found a still limited number of publications on the LCA of tall timber buildings in the Journal of Building and Environment. Although tall timber buildings have been a reality for more than two decades, their incidence lies predominantly in central European countries, Canada and Australia, which might be one reason for the past lack of publication on the subject. Nevertheless, this study showed a sudden increase of interest in the topic, demonstrated by the number of publications in the past two years.

It was also noteworthy that recent LCA studies tend to go beyond a single building lifespan, with extended time horizons evaluation to account for a more accurate assessment of biogenic carbon dynamics and its impacts on buildings and materials lifecycle. Likewise, topics such as design for adaptability, disassembly, and reuse and their influence on the LCA of taller timber buildings appear to become increasingly relevant for the field in recent and likely in the coming years.

Part 3

Durability

Sub Group (SG) 3

WG4.SG3.01

Durability of timber buildings – concepts, requirements and design

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1 Introduction

Modern architecture with the renewable material wood leads to impressive and demanding timber structures with high requirements for planning, production, logistics, commissioning, and use. Quality assurance during the construction and durability during the operational phase is crucial. The realistic estimation of the risks for all timber structure elements during the construction and operation phase, the risk of cracking, shape stability of the cross sections and long-term performance of connections are important points. With an increasing height of timber-buildings, the requirements of durability are rising as well. To avoid damages, the special characteristics of timber as a building material should be considered comprehensively. To evaluate, which topics regarding the durability are most relevant for the design of tall timber-buildings, the definition according to EN 1990 is given:

Durability means the ability of a structure or structural member to satisfy, with planned maintenance, its design performance requirements over the design service life

Based on this definition, several requirements can be specified depending on the point of view on durability:

- Structural engineering; to design the timber-construction and connections sufficiently against impacts, to meet the requirements of the structural integrity and serviceability during its service life.
- Architectural; means to have a floor plan of the timber building, which can easily be assigned and rearranged for different users (e.g., residual living, offices, school etc.).
- Chemically; to protect or improve the wood or the wood surface with suitable coatings or impregnations, e.g., moisture barrier, fire retardant
- Building physics; to ensure healthy and of high quality environmental indoor conditions

The focus is on the aspects of the structural engineer aiming to identify the most relevant points of the durability in load bearing behavior and serviceability. This includes timber as a building material, construction methods, specific experimental testing methods for long-term behaviour, and the climate impact.

2 Design criteria using wood as a building material

Every construction material has its specific challenges regarding the design and the construction. E.g. steel, must always be protected of corrosion and high temperatures; reinforced concrete is very sensitive regarding carbonation and the amount of water which is added to the mixture and the cracks which occur during the drying process. Wood is a naturally grown and climate-friendly building material. The relevant challenges of timber as a building material are considered in the following.

The topics of wood coatings, climate impact and moisture content, connections and monitoring are covered in the separate parts within this STAR.

2.1 Construction and Conceptual Design

In taller timber buildings, as in all other timber structures, durability must be a central point from the start of planning to careful elaboration of details. Priority must always be given to structural wood preservation. If wood is installed dry and kept dry during construction, it will last for generations. Today, according to EN 1990 we design structures for a service life between 50 and 100 years. It becomes clear, however, that tall buildings with a height larger than 20 m are not explicitly covered in the definition of EN 1990.

- Building structures and common structures, e.g. residential buildings: 50 years
- Tall buildings (H > 20 m): Not explicitly mentioned
- Monumental building structures, bridges, other civil engineering structures: 100 years

The assurance of a service life greater than 50 years requires the use of high-performance and approved wood products, the efficient design of connections and the consideration of climatic influences. Referring to the definition of durability, it becomes clear that the exchangeability of single components should be considered as well. As an example, a massive CLT ceiling could be evaluated as less durable than a ceiling made of several Glulam-beams, because then beams could be exchanged more easily.

2.2 Climate impact, moisture content

Wood and wood products as hygroscopic materials interacts with the ambient climate variations of relative humidity and temperature and leads to moisture content (MC) variations across the cross section. The moisture content is one of the important indicators for the quality assurance of timber structures. Because the MC affects the physical and mechanical properties as well as the dimensions due to shrinkage and swelling below the fibre saturation point (FSP), as shown in Figure 1. Due to constrained volumetric strains, e.g., due to swelling and shrinkage, changes in moisture content impose moisture induced stresses (MIS) which, if exceeding the tensile strength perpendicular to the grain of the material, can cause fractures such as cracks or delamination. Thus, the correct estimation of the MC is important for the design, quality assurance, and durability of timber bridges.

Moisture as a cause of structural failure was quantified by a study in which damage in existing buildings in southern Germany were assessed. Moisture accounted for half of the observed structural damage: too wet, too dry, or varying moisture conditions (Frese & Blass, 2011). The latter accounted for approximately one sixth of the damage in need of repair (Dietsch & Winter, 2018). About 90% of the encountered damage was found in glued laminated timber. The rest of the damage concerned wrong assumption of loads or erroneous calculation of load bearing

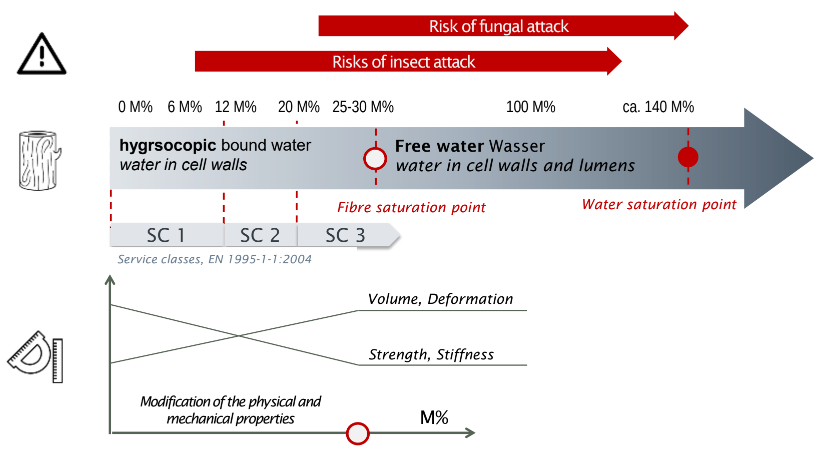

Figure 1: Presentation of the wood moisture content and its relationships to the moisture class, mechanical and physical properties and the hazards of the wood, Graphic developed by B. Franke

capacities for instance. Moisture content variations have been suggested as possible cause for total collapse in Frühwald et al. (2007).

Timber should therefore be protected as good as possible from moisture. This includes the assembly process as well as the final construction. If the timber gets wet during the building process and is then encapsulated which prevents a proper drying ("water trapping"), the moisture will probably never get out and the risk of fungi attack increases. Moisture entry could also take place through wet screeds or concrete, wetting the timber up to rates over 25%.

The typical „weak points" of the construction are, besides the construction phase, joints, cut-outs, windows, flat roofs, leakages in water-pipes or the sealing layers between wet rooms/modules. Possible solutions for prevention of those damages could be:

- Increase of prefabrication to shorten the assembly process
- Assign the correct expected moisture content for service time, preconditioning of timber elements during production process
- Proper protection of timber elements and construction during the complete assembly process, e.g., a temporary tent, see Figure 2
- Monitoring systems to control the climate respectively the moisture content in the building during the service life
- Monitoring systems for surveillance of leakages in waterproof layers, e.g., flat roof, wet room surfaces, ground conditions
- Protection of openings in the building envelope with grids/nets against insects.
- Consideration of structural wood preservation acc. to DIN 68800-1

Knowledge of the expected moisture content levels is important during an early design stage. It helps to determine allowable load levels and the expected deformations. A first indication is given through the system of Service Classes (SC) described in the Eurocode 5 (EN 1995-1-1, 2004). But this gives rough classes and architects, engineers and planners want to know what moisture content levels can be expected in (new) building types. Effective planning of protection against weather/precipitation could be performed by:

- Protection of the construction during transport and storage.
- Use of temporary roofs (highly recommended although expensive)
- Efficient sequential erection with direct implementation of the finishing façade and/or roof as weather protection.

The most important rules for inspection are summarised:

- In general, all structures and members must be closely checked. Sheeting/cladding needs to be opened and scaffolding or portable hoisting platforms should be used.
- Considering of days with rainfall for observation of leakages and water flow.

Figure 2: Efficient protection during night and weekend or rain event; removing of the protection during the working times (Swatch building, Biel/Bienne, Switzerland, Source: B. Franke)

2.3 Issues within life cycle, service time

Timber can easily be cut and processed which is a great advantage in most cases. In others, however, this leads to problems on the construction on site: Spontaneous adjustments, late involvement of building services, joints, openings and penetrations are typical reasons for damages, which arise during the service time. Possible solutions for prevention of those damages could be an early-stage communication with project partners, the premature planning of cut-outs and opening and a thorough quality-control on site. The costs of maintenance during the life cycle vary a largely, depending on the quality of the building, monitoring concepts and user behavior. A rough estimation for maintenance costs is 1% of the manufacturing cost.

2.4 Time-dependent material behaviour (creep and shrinkage)

Time dependent effects of wood, such as the creep-deformation, are a relevant issue for the design of structural members such as slabs in the serviceability limit state. These effects become even more relevant if composites, such as timber-concrete composites are used since not only the creep of the timber, but also the shrinkage of the concrete member must be considered. This can especially for taller timber buildings, which have a longer time for erection, open up new questions regarding a comprehensive design. A possibility to reduce shrinkage effects of the concrete are the use of prefabricated concrete parts as proposed by Frohnmüller and Seim.

2.5 Market value

In addition to the above-mentioned points on technical durability, it must be proven that tall timber buildings are in no way inferior to buildings made of other building materials to make them economically sustainable. To the extent of our information, the scope of the study of the market value of buildings in timber construction included buildings up to the year 2000 (Winter and Kehl 2022), thus also including modern houses built with the help of glue laminate technology. The authors recommend that in the determination of the mortgage lending value of modern, highly insulated, and quality-assured timber buildings, the same discounts should be used as for comparable solid [non-timber] buildings (Winter and Kehl 2022). It also points to studies that put the service life of timber buildings at well over 100 years. The study suggests a common total usage life of 80-100 years for calculating the market value of wood buildings in the 1985-2000 construction period. Therefore, we recommend applying the research method to the last 20 years to ward off the inferiority once again and to plan the lifetime expectancy of tall timber buildings technically with not less than 100 years.

3 Conclusions

The moisture content is one of the most important key parameter to consider. Regarding the timescale, the focus of engineers and architect is mostly on the use-phase of the building, although a lot of damages can be avoided by a better focus on the construction phase. The development of best-practice principles for the assembly process could be a solution.

The use of planar timber-parts (such as CLT plates or walls) is increasing. Damages due to moisture are therefore usually not visible until a total failure of the part occurs. The development of guidelines, how to use monitoring tools in a best possible way should be considered, because sensors usually measure only at singular points although the whole building is of relevance.

WG4.SG3.02

Durability of taller timber buildings – Wood coatings for exterior use

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1 Introduction

Wood plays a significant role in achieving the European climate goals, as it is carbon neutral, technically versatile, and available in large quantities across Europe. However, extended usage is hampered by wood's technical deficiencies regarding biodegradation, colour stability and fire safety. Wood coatings provide a great means to overcome these deficiencies and extend the service life of wooden building products such as facades, windows, balconies or doors. Nevertheless, coatings require improvement in several major fields of innovation. The most important topics can be specified as follows:

1. improvement of the long-term colour stabilisation of the wooden substrate and the coating
2. extension of the technical service life of coatings
3. Increased accuracy of service life prediction models
4. the substitution of petrochemical binders and conventional biocides in coatings with bio-based binders and natural biocides
5. the improvement of reaction-to-fire by bio-based, environmentally friendly and leaching resistant fire retardants

2 Long-term colour stabilisation of wood and coatings

Wood has a pleasing visual appearance. Therefore, architects and building owners often want the wooden building elements or the timber construction to be visible (Figure 1 a). This contrasts with other building materials such as concrete or bricks, which are usually coated by a decorative paint or surface finish. However, if wood is not properly protected by a coating in outdoor applications, photodegradation induced by light and humidity as well as

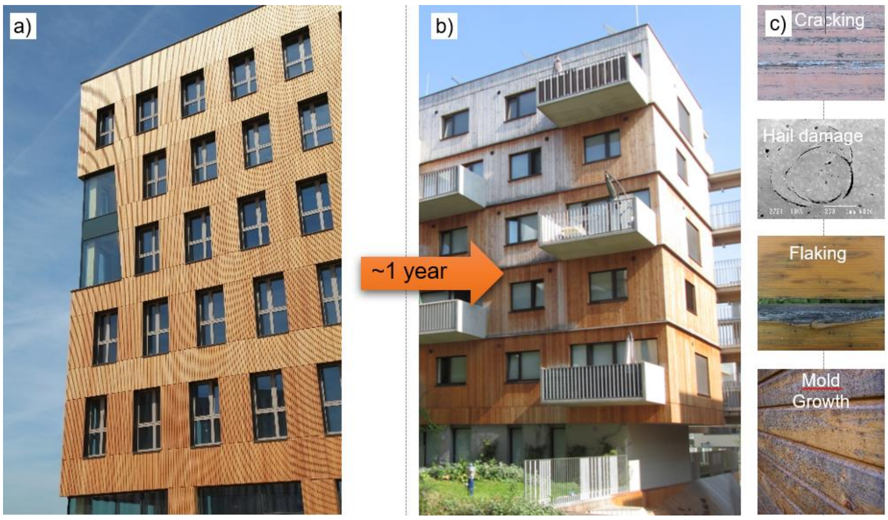

Figure 1: a) New facade of uncoated wood at HoHo in Vienna (2018), b): Seestadt Aspern, Vienna 2018, uncoated wood after one year of exposure with irregular discolouration; c) different coating damages: coatings are susceptible to damages and make frequent maintenance necessary, which is costly. Therefore, the scarce multi-storey buildings with wooden facades worldwide have left uncoated. This strongly limits the colour range in architectural design and may result in uneven greying.

biodegradation by microorganisms will lead to rapid discolouration of the exposed wood surfaces, turning the colour into a brown or grey tone. This is often undesirable, especially if the discolouration is uneven. There is a clear influence of the cardinal direction on discolouration, and partially sheltered surfaces have lower photodegradation rates (Forsthuber et al., 2022). This leads to uneven discolouration, e.g., underneath balconies or horizontal division sheets between fire compartments (Figure 1 b). Another important reason for discolouration are microorganisms, such as surface mould. This is of special importance in the light of climate change as a warmer and wetter climate promotes mould growth (Gobakken, 2010). All the reasons for discolouration mentioned above can be prevented by coatings. This however requires that they are intact and fully functional; this, however, requires regular maintenance, which is especially challenging for taller timber buildings. Leaving wooden facades uncoated has become popular in modern architecture, especially of large buildings like multi-story houses, in order to circumvent frequent maintenance, particularly repainting (Hundhausen et al. 2020).

Figure 2: Silver grey semi-transparent coating that will be replaced by natural greying.

To obtain a quick and even greying of a facade, a grey “sacrificial” stain can be applied that gives an even colour transition to natural greying during its degradation due to weathering (Podgorski, Georges, Izaskun Garmendia, & Sarachu, 2009), as shown exemplarily in Figure 2. There are several of such greying stains on the market. Alternatively, chemicals like bleaches or tannins with ferrous ammonium sulfate can be used (Hundhausen et al. 2020).
Details on the influence on the service life of coatings as well as service life prediction are given in the next section.

3 Technical service life and service life prediction

The service life of coatings should be as long as possible to reduce maintenance costs, ensure the best use of resources and provide long term storage of CO2. Additionally, maintenance costs are substantial, especially for taller timber constructions. At present, maximum maintenance intervals for exterior wood coatings are approximately 10-12 years with values up to 20 years for opaque systems and only 2-5 years for transparent systems (Grüll & Tscherne, 2020). The service life depends on the coating itself, the wood and the exposure conditions. Regarding the coating, its durability is influenced by many factors, mainly the binder chemistry, dry film thickness and pigmentation. It is important to distinguish between maintenance and renovation (Grüll et al. 2011). Maintenance is repainting, i.e., the application of one or more coats on top of an existing coating; in contrast; renovation requires the complete removal of the coating including the first cell rows of the degraded wood and the application of a full coating system, i.e., a primer and one or more layers of a topcoat. Maintenance is therefore much easier and cheaper to perform but requires the wood surface to be still intact.

3.1 Coating composition, dry film thickness and pigmentation

Coating binders are the backbone of a coating and have thereby a major impact on the service life of coatings. While oils and alkyd resins have the advantage of a high bio-based content, service life with acrylics and polyurethanes is usually higher. The dry film thickness is another important parameter for the service life. It was shown by Grüll et al. (Grüll, Tscherne, Spitaler, & Forsthuber, 2014) that higher film thicknesses lead to higher service lives. The pigmentation has also a high impact on the service life: opaque coatings provide the longest service lives (up to 20 years), while transparent coatings can have service lives of only 2-3 years. Regarding the colour of the pigmentation, higher service lives can be obtained with lighter colours compared to darker colours for opaque coating systems. This can be explained by the higher surface temperature due to higher light absorption by darker colours. It is well known that higher temperatures lead to higher degradation rates, thus decreasing the service live. For that reason, novel infrared transmissive “cool pigments” are available since recent years, that can decrease the surface temperature but retain a black appearance (Truskaller, Forsthuber, Oreski, & Grüll, 2018). In contrast, with semi-transparent coatings, darker colours lead to longer service lives compared to lighter colours. This can be explained by the higher absorbance and therefore higher light protection properties of darker colours. Hail damage is another issue, that can destroy a fully functional coating system within a few minutes (Grüll & Pastler, 2018).

3.2 Weather conditions

Weather conditions play a crucial role in the service life of coated wooden building products. Longest service lives can be achieved on vertical surfaces that are protected against direct exposure (e.g. underneath canopies). Shortest service lives are seen on horizontal surfaces with direct exposure to weathering. Regarding the cardinal direction, surfaces facing the equator have shorter service life than those facing to other directions. Another important factor is hail, which can destroy a fully functional coating system within minutes (Grüll and Pastler 2018).

4 Service Life Prediction (SLP)

The estimation of the service life of a coating requires to define the response variable. From a technical and economic standpoint, the time to maintenance, i.e., the time until the first maintenance coating has to be applied on the construction element, is a reasonable choice as carrying out maintenance is much easier and more cost-effective than renovation. Applying the maintenance coating in time can considerably extend the time for renovation.

Maintenance is required when the first cracks appear in the coating (Grüll et al. 2011). The time-to-failure states the time, until a limit state is reached. For wood coatings, a SLP model based on an adapted factor method according to ISO 15686-8 is available. The basis of this method is a reference service life that must be known in advance. This reference service life is then increased or decreased, depending on a variety of factors. The reference service life of a coating is the actual service life of a coating with known service life at a known location and known exposition conditions. In the SERVOWOOD project a service life prediction online tool was developed. The access to this app is restricted and can be requested by Carine Willems of CEPE (c.willems@cepe.org).

5 Wood coatings for exterior applications – increase bio-based content

Another important topic is the substitution of petrochemical binders and biocides in coatings. Most coatings for exterior applications are based on alkyd, acrylic or polyurethane resins. Especially the latter two are currently mostly based on petrol-based materials. The highest amount of bio-based content can currently be achieved with alkyd resins (up to 97%). However, this is not the case with acrylates and polyurethanes. 75% of the European Wood coatings are based on Poly(meth)acrylates and Polyurethanes. Though substantial progress has been made in the substitution of petrochemicals in binder technology, the bio-based content of commercial acrylic or polyurethane products is less than 80% (typically around 50%).

Growth of mould fungi with dark-coloured hyphae and spores (blue stain fungi) is a common phenomenon both on coated and uncoated wooden façades (Gobakken & Vestøl, 2012). While blue stain fungi pose no threat to the structural integrity of a building, moulds and blue stain fungi are often considered to be undesirable elements, especially on light-colour wooden façades (Gobakken & Vestøl, 2012). Since common microbicides such as propiconazole and IPBC are under high legislative pressure, alternative strategies for biocontrol are needed. The research on substitution of conventional biocides with more environmentally friendly ones that still stabilize wood against biodegradation focus mainly on living plants that produce chemical compounds that fend off intruding microorganisms. The natural durability of wood is very often related with its toxic extractive components (Nascimento et al. 2013). Tannins, flavanoids, lignans, stilbens, terpenes and terpenoids can be listed as major extractive chemicals and are well known with their protective properties against biological degradation of wood (Gerengi, Tascioglu, Akcay, & Kurtay, 2014).

6 Fire protection

A critical point of many fire-retardant chemicals (FR) in outdoor applications is their poor fixation in wood. They are prone to migration due to moisture changes, which bears the risk of salt crystallisation on product surfaces often associated with coating failures and, at worst, loss of the FR (Östman 2010). In 2017, this issue was addressed by the standard EN 16775, which prescribes the testing and classification requirements for the durability of reaction to fire performance. This means in other words that the standard provides a classification system that specifies the resistance of an FR to leach from wood in humid conditions. According to EN 16775, FR-treated wood in outdoor applications, such as facades, must fulfil the requirements for DRF Class EXT. The FR-treatment can either be an impregnation or a coating application. In case of facades, both application types are usually carried out in industrial processes. There are currently only a very few impregnation agents on the European marked that allow wood products, such as cladding, to obtain DRF Class EXT without a protective coating that hinders leaching. Such an FR was for instance used for protecting the facade of the world's tallest timber building, called Mjøstårnet, located in Norway. However, DRF EXT can also be obtained with less moisture-stable FR-impregnants, but only in combination with a non-flame-retardant paint (referred to as ordinary paint in EN 16775) that protects the FR from leaching. This solution implies frequent maintenance, i.e., repainting, of the facade. The same applies to the third solution to obtain DRF Class Ext, which is to use an FR-coating. In this case, the wood product does not need any impregnation treatment.

7 Conclusion

Wood coatings can extend the aesthetical and technical service life of wooden construction products but require regular maintenance. The application of maintenance coatings in time are the key to extend the service life considerably. If the point of time for maintenance is missed, renovation, i.e. removal of the coating and the application of a full coating system, is required, which is very costly. The technical service life can be extended by the right choice of coating system and sheltering but this is sometimes in conflict with aesthetical considerations. SLP-models are available that can predict the time for maintenance. Improvements are required in terms of extending the service life, developing novel fire retardants as well as changing the raw material towards bio-based resources.

WG4.SG3.03

Assessing the durability of adhesively bonded timber-concrete composite structures

Jens Frohnmüller, University of Kassel (Germany)

1 Introduction

The construction of tall timber buildings without the use of adhesives is difficult to imagine. The use of wood products (Glulam, CLT, LVL, OSB, …) is widely established and most wood products contain adhesives. Because wood products often take over important load bearing elements in the construction, the adhesive bondlines must full-fill high regulations. Therefore, the requirements on the adhesive joint are that over the expected lifetime no loss of adhesion strength of the surfaces occurs and that the whole product or element upholds its functionality.

In this context it is important to mention, that some aspects of the durability can neither be calculated nor modelled, they must be assessed experimentally. The challenge hereby is to ensure the durability of the adhesive joint over the expected lifetime (> 50 years) in a limited amount of time (approximately 1 year).

Lately, not only wood products, but also composite structures such as timber concrete composites (TCC) gain importance due to their advantages in stiffness, strength and buildings physics. If adhesives are being used to bond timber and concrete, it is possible to use prefabricated concrete parts instead of freshly applied concrete. Adhesively bonded timber-concrete composites are, however, no standard yet. To ensure the durability of this joint nevertheless, it is expedient to adapt existing test-methods for the assessment of the durability and apply them on the new joint if possible.

2 Assessing the durability

2.1 Test methods for adhesively bonded timber connections

The requirements for the adhesive are summarized in EN 301:2006 and relate on the one hand to the properties during the application ("wet" adhesive), on the other hand to the properties of the cured adhesively bonded connection.

With reference to EN 302-2:2004, part 1 to 8, the adhesive is usually tested in different combinations of mechanical loading and varying climate (moisture and temperature), mostly in quasi-static tests. A common long-term test method for adhesive connections can be found in DIN EN 14516-1, where test-specimens are stored for up to one year in a climate chamber or a green house, strained by constant mechanical loads and varying climate.

A possible rapid test to check the integrity if the adhesive bond is the delamination test according to EN 302-2. There, the specimens are forced to swell and shrink under extreme conditions in a very short amount of time.

2.2 Test methods for adhesively-bonded timber concrete composites

Adapting the common test methods for timber proves to be challenging because concrete-parts cannot be sawn as easily as timber and the adhesive joint is usually thicker than common timber-to-timber bondlines. Furthermore, the specific surface of the concrete part, which is defined either by the formwork used for concreting or the sandblasting, should also be considered. To uphold the concepts of the specific tests from section 2.1, it is often necessary to modify the specimen geometry. Frohnmüller et al. 2021 presents results, where the approach of EN 302-8 is adapted on adhesively bonded TCC specimens. Two different types of specimen were manufactured according to EN 14080 and according to EN 408 and both series were stored in a climate-chamber and strained with constant shear loads. The results indicate that the bondline is durable in a sufficient way, although open questions remain, if the results were influenced in a negative way by tensile stresses perp. to the bondline.

Frohnmüller and Seim 2021 further present a test-method, where the delamination test according to EN 302-2 is adapted. The specimens with a thick bondline and a highly-filled adhesive show a favourable behaviour while the specimens with a thin bondline and a standard epoxy adhesive lead to an early substrate failure in the adherents. Although the adhesion-strength of this epoxy adhesive proves to be sufficient, it is questionable if the functionality of a thin bondline can be guaranteed.

The results indicate that not only the adhesive itself, but also the adhesive connection (adhesive, contact surface and adherent) should be included in the considerations of the durability.

3 The effect of creep and shrinkage on stresses in the bondline

Time-dependent material behaviour of timber and concrete such as creep, shrinkage and relaxation influence the composite beam in several ways:

1. Increase of the long-term deformation.
2. Increase of the bending stresses in the timber. Schänzlin (2003) points out that loads are “transferred” into the timber part in the time range of 3 to 7 years because the shrinkage of the concrete takes place faster than the creeping of the timber.
3. Increase of bond stresses at the end of the beam due to shrinkage of the concrete.

Regarding the first issue can be said, that the long-term deformation of adhesively-bonded timber-concrete composites can nowadays be calculated by several calculation methods. Eisenhut et al. (2016) and Tannert et al. (2020) present different calculation methods with a high correlation between experimentally determined long-term behaviour and calculation.

Regarding the second issue, a design procedure is proposed in CEN/TS 19193:2021 for this specific case. A validation of the regulations from CEN/TS 19193:2021 for adhesively bonded TCC is pending.

Regarding the third issue: With an advancing shrinkage of the concrete, the bond stresses of the concrete at the end of the composite beam are increasing as well. The extend of the increase can be calculated with FE-models. A FE-model, which has been validated with the parameters of the moisture content in the timber and the long-term deformation of the composite beam, has been presented by Eisenhut et al. (2016). Kühlborn (2016) further shows that the shear stresses are increasing and decreasing after some years again, see Figure 1.

The extend of the shear stresses depend on the age of the concrete. The shorter the time between manufacturing of the concrete and gluing is, the higher are also the shear stresses. The largest shear stresses can be expected, when the concreting and the gluing are carried out together. This procedure, where in-situ concrete is applied on fluid and reactive adhesive is known as the wet-in-wet gluing method. Arendt et al. (2022) published results of the wet-in-wet gluing method and lightweight concrete where bond failure took place in the first weeks after concreting without any outer loads. The failure took place because the stresses due to shrinkage exceeded the bond strength of the concrete.

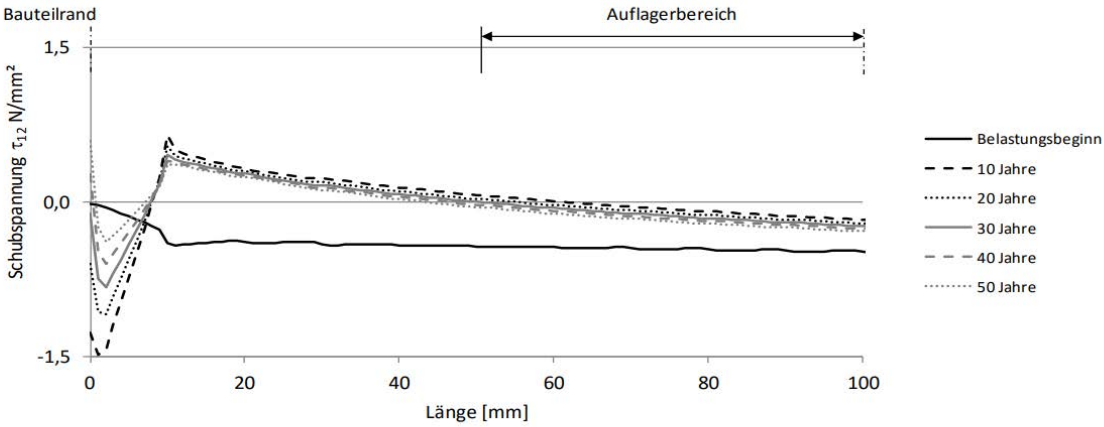

Figure 1: Development of the shear stress at the end of an adhesively-bonded timber-concrete composite beam with prefabricated concrete parts over 50 years. Source: Kühlborn (2016)

Although no such damages have ever been documented with prefabricated concrete parts, the relevant question to raise is: what are the minimum requirements to ensure, that no premature failure in the bondline takes place regarding the

- required time between concreting and gluing.
- required strength of the materials.
- type of adhesive.
- thickness of the bondline.
- arrangement of the bondline (continuously or discontinuously).

4 Conclusions

Adhesively bonded timber-concrete composite structures could be an interesting alternative to mass timber slabs in tall timber buildings, because the construction time can be shortened significantly using prefabricated concrete parts.

The adhesion strength of the bondline can be assessed experimentally in different short- and long-term tests, where the bondline is strained by a combination of mechanical loads and different climates (moisture and temperature). The

Regarding the functionality of the adhesive bondline, the results in the literature indicate that besides the adhesive itself, the thickness of the joint and the filling of adhesive are important factors. Moreover, the functionality is also defined by the stresses which occur at the end of the beam due to the shrinkage of the concrete. First approaches to calculate this phenomenon are available in literature and successful material combinations and manufacturing methods have been published. Systematic research on this topic including different parameters has not been carried out yet.

WG4.SG3.04

Seventh-year durability analysis of post-treated wood-based composites used in wooden buildings

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1 Introduction

The production of wood-based composites (WBCs) has increased considerably over the past few decades and they have been utilized under conditions conducive to biological attacks. Unfortunately, these composites are prone to decay fungi and termite attacks if utilized without preservative treatments. There are two major procedures to protect WBCs and WPCs. The post-manufacturing treatment is applied after the production of such composites and does not require any modification in composite manufacturing lines while some side effects on mechanical properties are reported. In-line treatments, incorporating biocides during the manufacturing process, might require some modifications on the manufacturing process but provides full protection throughout the board thickness.

1.1 Materials and Methods

Alkaline copper quat (ACQ) and copper azole (CA) which have been accepted worldwide as alternatives to chromated copper arsenate (CCA), were evaluated as wood preservatives for post-manufacturing treatment of WBC in the present research.

Specimens were prepared from five commercially available structural-use wood-based composites: softwood plywood (SWP), hardwood plywood (HWP), medium density fiberboard (MDF) produced from hardwood fibers, aspen oriented strand board (OSB) and particleboard (PB) made of both hardwood and softwood particles. The specimen sizes were 100 mm x 100 mm x thickness for field tests. ACQ and CA were tested for their effectiveness at three retentions, respectively K1, K2 and K3 classes as designated by JAS.

Untreated and treated wood based composite specimens were tested for their changes in mechanical properties due to preservative treatments by the JIS three-point bending method. A previously developed system to simulate performance of sill plates (dodai) in traditional Japanese homes was used in the field tests.

Table 1: Manufacturing details of wood-based composites tested.

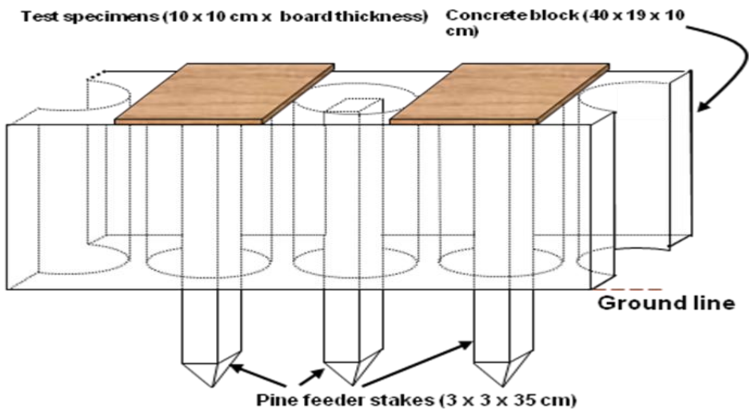

Figure 1. Installation details of specimens and feeder stakes in the Living Sphere Simulation Field (LSF) of RISH, Kagoshima, Japan

Composite	Raw material	Orientation and construction	Adhesive
SWP	***Larix* spp.**	**0º/90º, 5 plies (2+2+3+2+3 mm)**	**Boiled-water resistant exterior type phenol-formaldehyde**
HWP	***Dipterocarpaceae* spp.**	**0º/90º, 5 plies (2+3+2+3+2 mm)**	**Boiled-water resistant exterior type phenol-formaldehyde**
MDF	**Hardwood fibers**	**Random, 3 layered (2+8+2 mm)**	**Melamine-urea-formaldehyde**
OSB	**Aspen**	**Random, 3 layered (3+6+3 mm)**	**Phenol- formaldehyde**
PB	**Hard/Softwood mix**	**Random, 3 layered (3+6+3 mm)**	**Melamine-urea-formaldehyde**

1.2 Results

The findings indicate that wood-based composites tested are not durable enough, even in protected above ground conditions, if they are used without protective treatment, with the exception of MDF. MDF displayed high natural durability and might be used under less hazardous conditions based on 7-year exposure data. Post treatment with ACQ and CA at the retention levels tested significantly enhanced termite resistance of SWP, HWP, OSB and PB but failed full protection at the end of 84 months period.

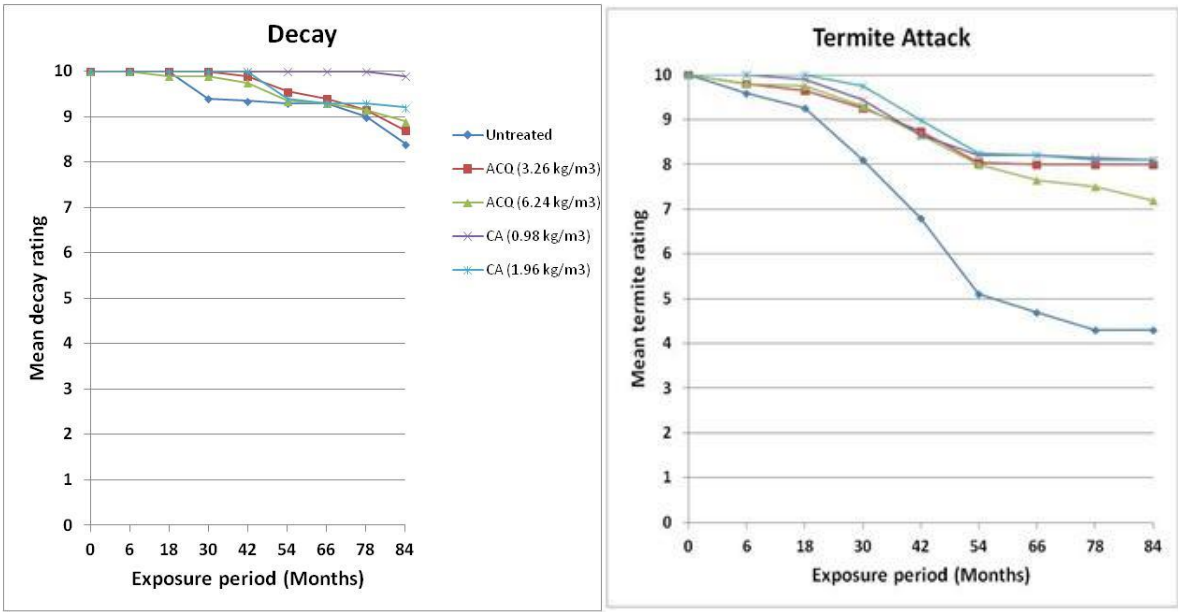

Figure 2: Progress in decay and termite attack for softwood plywood (SWP) during 84 months of exposure.

WG4.SG3.05

Durability of timber connections

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1 Introduction

In contrary to steel or concrete buildings, the performance of a timber building is significantly defined by the stiffness of the connections. The design of those connections for residual buildings has been covered quite comprehensively by COST Action FP1402, WG3 with a focus on functionality, strength, and stiffness. Comparing tall timber buildings with residual timber buildings, however, there are

- higher loads (vertical and lateral).
- higher necessity looking on fatigue.
- more inspection and maintenance, see COST Action FP1101.
- limitations regarding the design, because not all materials and construction methods (e.g., ceilings made of timber beams) are suitable.
- further design criteria, such as a possible consideration of deformations from compression perpendicular to the grain, see Windeck and Blass (2022).
- critical design points which are not common to consider, such as the deformation resulting from different settlements of concrete shafts and timber-constructions.
- newly arising questions with an increasing size and number of reinforcements such as shown by Danzer at al. (2020), who found a reduction of the load-carrying capacity of about 65 % - 83 % due to the restraining effect with an increasing number of reinforcements and size.

Those aspects open new questions regarding the durability of tall timber buildings.

2 Influence factors of the durability

2.1 Time, temperature and climate

The consideration of long-term effects and strength losses are possible with the parameters k_{mod} and k_{def}. If timber-concrete composite (TCC) structures are used, the consideration of creep and shrinkage is crucial as outlined in CEN/TS 19103. Creep can be taken into account with a reduction of the E-modus of the materials, shrinkage as an own load case.

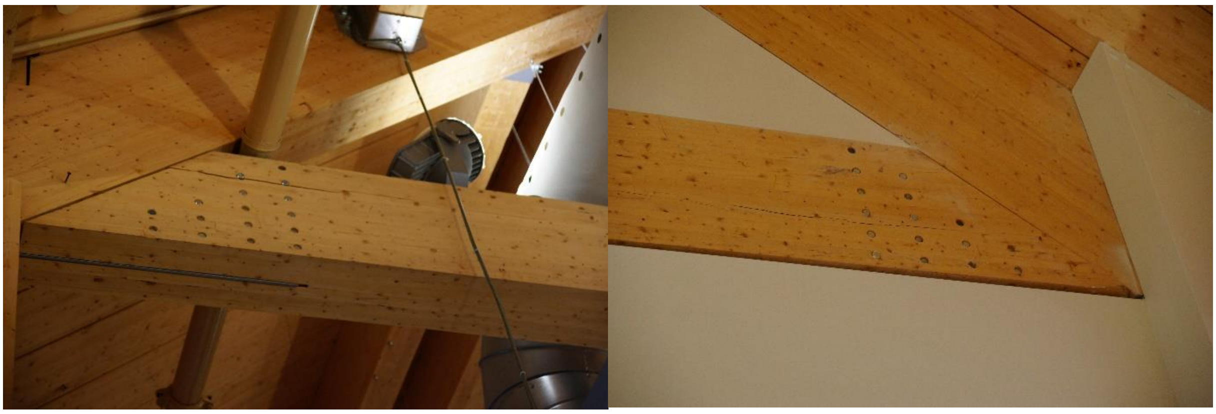

Figure 1: Cracks in the area of connections due to restraining effects

2.2 Moisture

Moisture accounted for half of the observed structural damage, see Frese & Blass, 2011. Planning and controlling moisture content during transportation and assembly is therefore an important factor. To reduce the risk of moisture damages, timber should be installed with the moisture content that is also expected during the use of the construction (EN 1995-1-1:2004, section 10.2 (3)). This would require a moisture content during the time of the assembly in the range of u = 12%.

Tall timber buildings are characterized by longer building phases, due to the absolute height of the building, but also due to the installation of the slabs. The slabs are oftentimes constructed as mass timber (MT) slabs or timber-concrete composite (TCC) slabs. Regarding MT slabs, moisture could be soaked into the wood when it is not protected consistently, possibly resulting in further damaged. For TCC slabs, usually in-situ concrete is needed, resulting in longer building phases because reinforcement must be laid, and concrete must be poured in freshly. A possibility to reduce the risk of moisture entry into the construction can significantly be reduced by using prefabricated concrete parts in TCC systems, enabling to uphold the advantage of a short construction time of timber and combining it with the advantages if a composite structure, see Frohnmüller und Seim (2021).

Regarding connections points, ventilation should be considered for all details, especially the important ones. Considerations are to include enough space to prevent capillary flow, include dripping rims, etc. as stressed by both Burkart & Kleppe (2017) and Bachofer & Conzett (2013). Once details are also easily accessible or enough space around them is provided, these can easily be cleaned and inspected if necessary.

2.3 Material

The choice of material should be closely considered when possible so that durability of connections is increased. Condensation grows on cold surfaces (Burkart & Kleppe, 2017). This can prevent needless accumulation of moisture of increased humidity around the connections. The choice of material could also involve choice of more resistant wood type for details with higher risk of decay.

2.4 Cyclic action

Cyclic action, or rather dynamic loading impact can be considered with the parameter k_{fat} according to EN 1995-2:2004, Annex A. If cyclic action must be considered for tall timber buildings, where higher loads and also higher lateral loads occur, depends on the construction, on the impact and on the type of connector which is used, see EN 1995-2:2004, A.1. Regarding notched TCC-systems, Mönch and Kuhlmann investigate the influence of cyclic action on the strength of the connection.

3 Design principles and best-practice examples

A safe and robust design of timber connections is the foundation for a durable construction. Some general design-principles to prevent damages are:

- Safe design and construction (Strive for compression stresses / avoidance of tensile stresses or concentrated stresses if possible).
- Strengthening with screws or glued-in rods.
- Consideration of restraining effects.
- Consideration of the edge distances acc. to EC 5, EN 1995-1-1:2004 or the specific product regulation of the connector.

- Consideration of accidental loading situations such as earthquake.
- Protection of the timber structure and the connectors from moisture and from fire.
- Quality-control on the construction site, Check for accreditation of connectors.
- Use of galvanized screws, bolts and metals.
- Control of the maximum size of timber connections, which is not limited in European standards.

Best-practice principles can be found at Infoholz (2022), a catalogue of proven and reliable constructions in CAD-format can further be found on Dataholz (2022).

4 Conclusions

Since the requirements of the durability are increasing with the height of the timber-buildings, several aspects of the durability of tall timber buildings should be targeted more specifically.

Size effects and moisture induced stresses affect the performance of the whole connection. For example: Not controlling the maximum size of timber connections can lead especially in shear connections with slotted in steel plates to high moisture induced stresses which can exceed the timber strengths. The application of reinforcements in these connections could help. The restraining effect of reinforcements, however, also increases with the size of the timber and the amount of reinforcement elements. Research on this topic is still needed.

Higher timber buildings and higher lateral loads can, at some points, result in a complex combination of cyclic and static loading of the connections. Combining these aspects with moisture induced stresses – which also can result from the longer building phase due to the increased height – opens questions if the current regulations are sufficient. A validation of current regulations is pending.

WG4.SG3.06

Holistic aspects and frameworks of lifecycle durability: climate change, sociotechnical robustness, and design for longitudinal learning

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1 Introduction: climate change, innovation and lifecycle durability

Climate change is a significant long-term change in the global and local microclimate. The development of climate change can be seen accelerating in the last 30 years. Climate change may also accelerate, or other global-level changes may occur as it progresses at numerous critical tipping points leading to global-level effects that are difficult to predict. The effects of climate change may vary by region and depending on the season, are diverse, and affect the built environment not only directly but also with a delay. It is important to understand that climate change does not mean steady warming, but an increase in extreme conditions with increasing variability of locally critical combinations.(IPCC WGII, 2022; Larjosto et al., 2021)

Coordinated climate change-related efforts are generally divided in the direction of climate change mitigation (CCM) and climate-resistant development (CRD). It is important to understand that all mitigating measures do not necessarily mean improving the resilience of buildings, i.e. the ability to adapt to climate change, but balancing these mitigation and adaptation goals constitutes a strategic level decision-making task, both on the scale of individual assets, larger portfolios and entities.(CISL, 2019; Hirsch, 2016; IPCC WGII, 2022)

Climate change mitigating measures (CCM) include socio-technical changes that improve, for example, energy efficiency (Christersson et al., 2015), fossil-free energy production, the use of low-emission materials (Skullestad et al., 2016), and extending the life cycle of buildings and their parts by means of quality and design requirements (Acharya et al., 2020), as well as by developing predictive maintenance (Faiz & Edirisinghe, 2009) and circular economy methods.(IPCC WGII, 2022) Aspects of circular economy (Ellen McArthur Foundation, 2019; UKGBC, 2019) and other sustainable construction methods, such as re-use of building components and adaptability (ISO 20887:2020, 2020), partly overlap with the CRD and are likely to have an impact on structural design solutions.

In the sense of adapting to climate change (CRD), we must talk about a future that is increasingly difficult to predict (Croce et al., 2018; Hirsch, 2016; Liu & Coley, 2015; Melin et al., 2018; Szumilo et al., 2016). In this case, the effect of a single measure or instruction on different aspects of durability can be positive, neutral/useless or even negative, depending on the context and the realized future scenario. Coping in complex environments primarily requires knowledge of risk management based on scenario work across material science, engineering, maintenance, land planning, finance and insurance, socioeconomic and organizational domains.(Akanbi et al., 2018; Burroughs, 2017; CISL & Deloitte, 2021; Galle, Waldo; De Troyer, Frank; De Temmerman, 2015; Hopfe & Hensen, 2011; Larjosto et al., 2021; Nofal & van de Lindt, 2020; Sousa et al., 2015; Wang et al., 2019) The definition of scenarios therefore requires the organization of closer cooperation with more diverse experts and stakeholders than before, as well as the consideration of long-term risk management as part of business reporting.(IPCC WGII, 2022; Ympäristömerkintä, 2021) In regard to structural engineering, some aspects of CDR are likely to become an integrated part on national and/or international structural design codes before 2030. However, during nearest decades the lifecycle durability should likely be addressed and verified using iterative and dialogic approach. Following chapter presents individual frameworks that can be used to outline CDR-informed lifecycle robustness strategies.

2 Sociotechnical frameworks and tools for lifecycle durability

Hagentoft, Ramos and Grunewald (2015, p.7) define *framework* as “guidelines, flowcharts and similar step-by-step instructions for determining a course of action” that can be “changed and adapted to specific tasks”. In this chapter, we cover frameworks that are proposed for different aspects of anticipated circular value chain of timber construction. Number of such frameworks and methodologies exist that can be harmonized and reapplied to the purpose of ensuring consistent reporting of lifecycle structural durability in taller timber buildings.

First important element of iterative risk management and capacity development process is the ability to capture, distribute, and update not only *formal*, but also *tacit knowledge* (Pathirage et al., 2007) belonging to different parties in buildings’ construction, maintenance, modification and renovation processes. Collecting tacit, location-specific and experience-based information is perhaps the most demanding task in terms of information management in the built environment (Delias et al., 2015; Howard & Bjork, 2007; Nordin et al., 2010; Rasmussen et al., 2019; Senaratne & Sexton, 2012; Tetik et al., 2019). As an established example, the *Soft Landings* framework (UK) supports the follow-through of the original design specifications by “*aligning the interests of those who design and construct an asset with those who subsequently use it*” (Rowland, 2014). Soft Landings is a strategy aimed at the development of the dialogic process, which can be used individually or alongside and as a method complementing the international standards (UK BIM Framework, 2019) *ISO 19650 Organization and digitization of information about buildings and civil engineering works* (ISO 19650-1:2018).

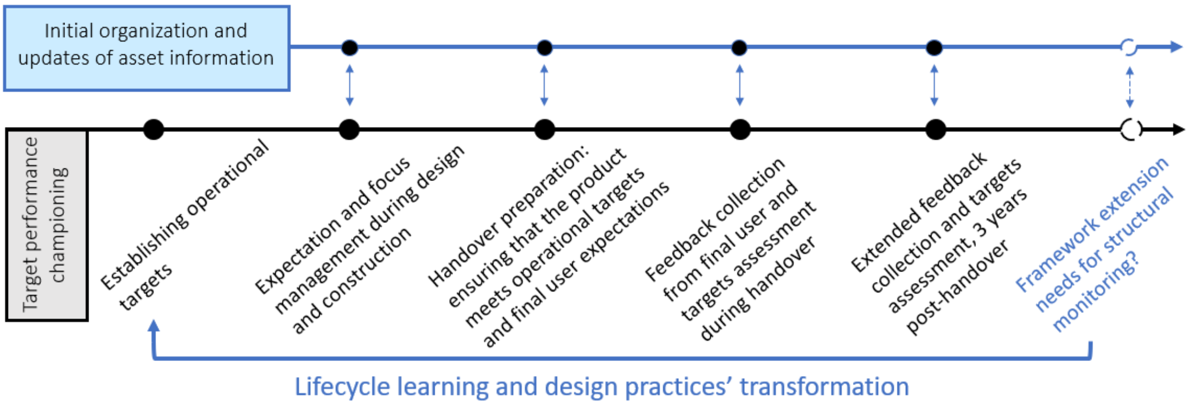

Figure 1: Soft Landings and ISO 19650, basic outline (authors’ summary)

Apart from existing formal and tacit knowledge, innovative projects increasingly require learning ability and efficiency, as well as resilience to unexpected challenges. Humane ability to withstand such mental loading should be accounted for. The 2007 summary of 127 forensic investigations of issues in timber structures emphasizes that human error is so common as a cause of documented structural failures that it "cannot be avoided by increasing the formal safety level in structural design" (Frühwald et al., 2007, 8). New sociotechnical methods addressing the structural durability issues by means of improved robustness of integrated delivery and maintenance teams’ workflows should be explored.

Dynamic competence management may include process-driven and substance-driven aspects. In *process-driven competence management*, such as Horizon scanning(Mark et al., 2018), the aim is to listen with a sensitive ear to the project staff’s concerns related to the quality and long-term durability. Where these concerns, combined with time pressures, raise the project's stress levels, the possibility of human error also increases.

The basics of *substance-based competence management* are developed e.g. as EU-level INSTRUCT project (Mäkeläinen, 2021; *INSTRUCT, n.d*). As a few examples of the wider innovative procurement methodology:

- in *pledge-based innovative procurement*, tender bids should be based on a verifiable level of performance
- *commenting on design proposals* can be included as part of the bidding process
- a *project-specific workshop exam* organized and assessed to clarify the key personnel's performance on the case tasks instrumental for the successful implementation of the project.

Competence must also be managed systematically, for example by discussing and allocating sufficient resources for dedicated learning.

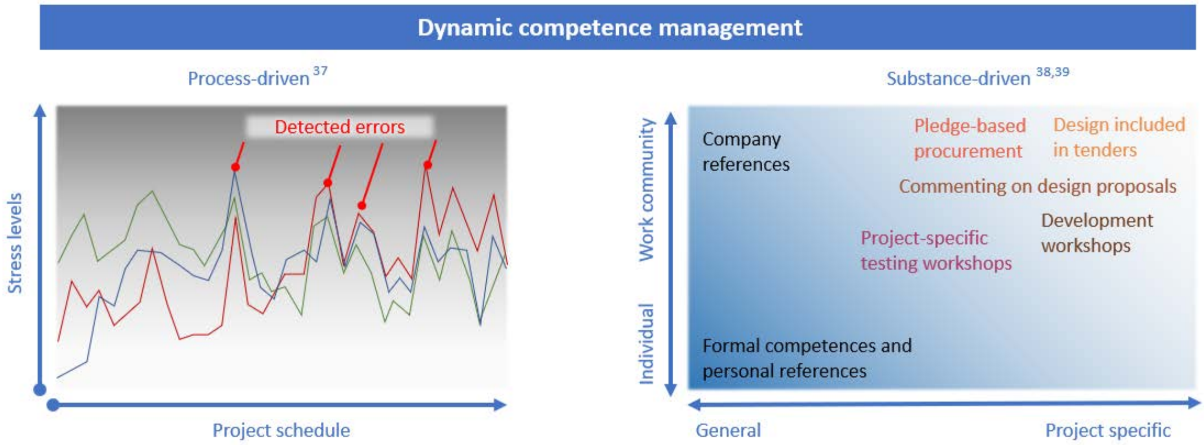

Figure 2: Dynamic competence management methods, basic outline

In the development benefitting from large-scale cooperation and data utilization, a framework for safety assessments of energy repairs in buildings (Hagentoft et al., 2015) can be utilized. This operational framework for probabilistic risk management of energy repairs, developed by the international energy organization IEA, is a part of climate change mitigation measures, but can be likely adapted for CRD purposes. The framework guides the utilization of statistical and computational information as a continuous learning platform for construction industry professionals. In order for energy repairs to be successful, a clear understanding of what the target level of energy consumption is and what kind of risks new structural solutions can tolerate is needed. In terms of the accuracy of these estimates, the significance of the statistical information collected from the area and from the same type of objects in different areas plays a decisive role. Within the project, the instructions presented in Annex 55 of the IEA's RAP-Retro project propose to follow the framework of iterative risk management according to SS-EN1050:1996 in group work. When the project is implemented, its results are compared to the target level, and positive deviations can then also be investigated for the benefit of continuous development and learning.

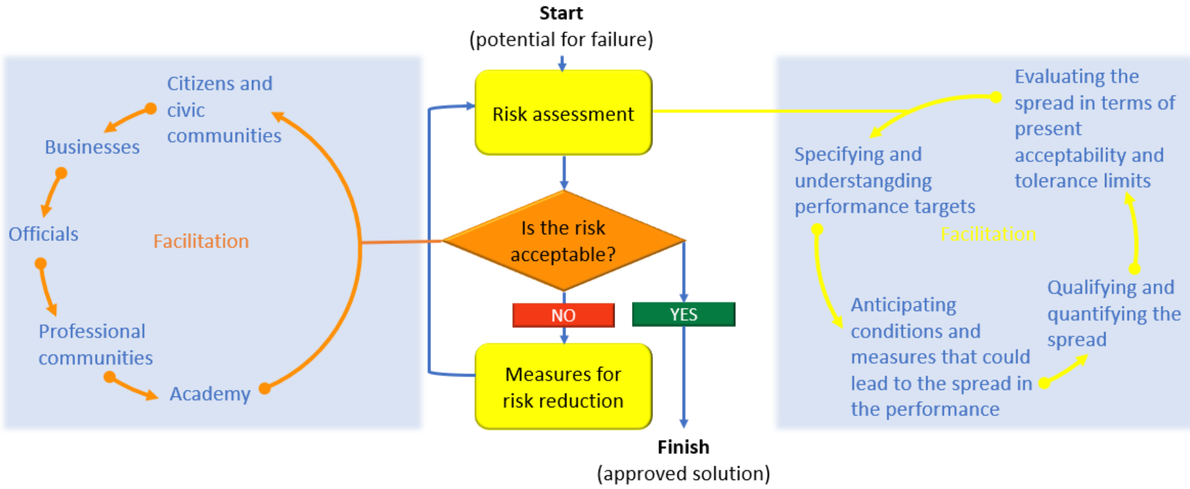

Figure 3: Dialogic and probabilistic methods of risk management (Hagentoft et al., 2015; Larjosto et al., 2021), basic outline (authors' summary)

On the interface between the built environment and ICT technology, the potential of utilizing the probabilistic assessments and rich sensor data to inform structural durability for purposes of responsible real estate value management and green financing is outlined in three mutually complementing directions.

- Information from the condition assessment of building parts in circular economy applications (Acharya et al., 2020; Arup, 2020; Luoma et al., 2021)
- Energy renovation and condition monitoring of energy-efficient solutions (Christersson et al., 2015; Hagentoft et al., 2015)
- Monitoring of innovative structural engineering solutions in real estate value management (Aloisio et al., 2020; Leyder et al., 2016).

The potential of the *digital twin* (DT) can be explored in the light of previous studies that proved the benefits of DT in applications combining data analytics and simulation (West et al., 2021). DT can be utilized not only as a storage of design information, but also as a platform for multidisciplinary cooperation in the lifecycle predictive maintenance of buildings (El-Diraby & Sobhkhiz, 2022). The ability to develop DTs as functioning and profitable lifecycle collaborative platforms requires ease of technical considerations' translation to business context. Such translation may offer multiple perspectives to an issue through data aggregation and visualization (West et al., 2021). Achieving the benefits does not necessarily or immediately demand a particular Digital Twin technology or even Digital Twin in its most complete form, however the sociotechnical objectives should be followed through from the earliest stages of the projects, applying data management principles like *Gemini principles* (Bolton et al., 2018) and advanced managerial framing and planning approaches such as *Service Dominant Logic* (SD-logic) (Camposano et al., 2021; West et al., 2021).

From the point of view of enabling alignment of structural durability objectives with holistic climate change resilience, it is also important to facilitate cooperation with building- and area-specific observations and general plan level risk management. For example, geospatial data-based risk mapping and regional vulnerability profiles will probably become more common as tools for combating extreme weather phenomena (Larjosto et al., 2021)..

Part 4

Moisture Impact

Sub Group (SG) 4

WG4.SG4.01

Methods for the monitoring of wood moisture content in taller timber buildings

Steffen Franke, Bern University of Applied Sciences (Switzerland), **Bettina Franke**, Bern University of Applied Sciences (Switzerland)

1 Introduction

The moisture content of wood is one of the key elements for the quality assurance during production, erection and service time of timber structures.

"Wood properly protected and controlled is very powerful and durable."

Therefor continuous monitoring of wood moisture content is a suitable early warning system. The importance of wood moisture in relation to possible damage in timber construction is shown in a study of Frese & Blass (2011), where 50% of all investigated objects show damage or failure due to wood moisture changes or low and high wood moisture contents. Another study by Dietsch & Winter (2018) shows that 30% of these objects are damaged due to seasonal or climate-induced wood moisture changes. Since the distribution of wood moisture is often not constant across the cross-section, internal stresses perpendicular to the grain (moisture-induced stresses, MIS) arise due to the anisotropic moisture-strain behavior. These stresses can easily exceed the characteristic tensile strength perpendicular to the grain and lead to crack development, Möhler & Steck (1980). In curved glulam beams, these stresses can also directly lead to the total loss of load-bearing capacity, as shown in Aicher et al. (1998) or Gustafsson et al. (1998).

2 General to the measuring methods

For the measurement of wood moisture content in taller timber buildings, single point and laminar measuring systems can be used, see overview in Figure 1. For the monitoring of small critical areas, the resistance measuring method, the sorption isotherm method and the passive RFID tag method are available. The principal description of the measurement techniques for wood moisture content is given in Dietsch et al. (2015) or Franke et al. (2019). Specifics for monitoring purposes for taller timber buildings are added below.

For local observations, the electrical resistance measurement method is technically very simple to implement, easy to install and can be replaced from the outside. The sorption isotherm method provides high accuracy by measuring relative humidity and temperature in

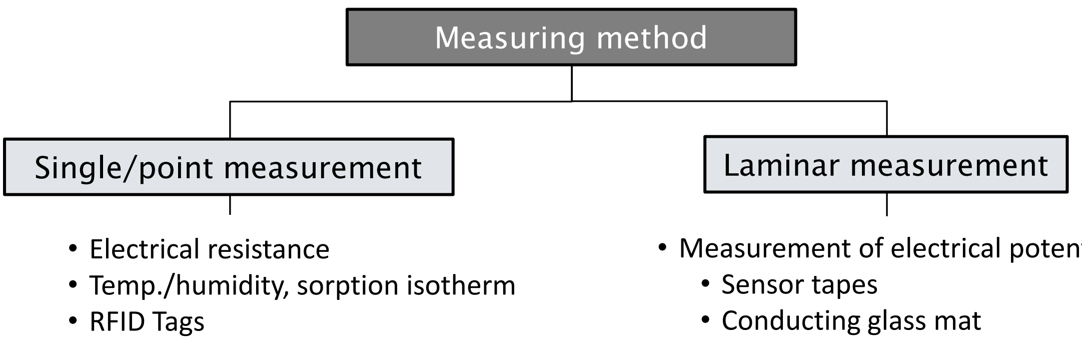

Figure 1: Overview of selected measurement methods for wood moisture content in the monitoring application, Franke et al. (2022)

an insulated cavity, Schiere et al. (2019). The electrical and sorption isotherm method can be combined with a data collection and managing plan as well as an automatic early warning system.

For a local temporary measurement, RFID tags are an option too, Franke et al. (2022). RFID tag measures the humidity in the immediate vicinity of the tag averaged over a certain component depth using the principle of capacitive sensing. The use of RFID tags is inexpensive and wireless. Passive RFID tags do not require an external power supply or battery and can be used in many applications, Smiley (2019). However, a handheld device is required to read the values at inspection time. Up to know there is no automatic continues measuring possible.

For the quality assurance of laminar elements like flat roof structures, inter layer of wet rooms/ toilets/bathrooms or basements from wood, two dimensional methods are available. This method detects an increase of the moisture content due to leakage surveillance but not a specific value of the moisture content.

Two-dimensional components can be reliably monitored with conductive glass fleece or with tape sensors. Both solutions rely on potential measurements and are mainly used in building construction for monitoring flat roofs, Burger et al. (2018), Franke et al. (2022). When the humidity changes or when water is present, the electrical potential of the conductive fabric changes and one can perform a real time moisture monitoring, Müller et al. (2021), Rödel (2022).

In monitoring systems, a distinction is made between two main groups in the sensors, the active and passive sensors. This designation is used to distinguish whether the sensor requires electrical auxiliary power for the measurement or not. Active sensors require a supply voltage and then generate an output signal. This group includes, among others, the sorption isotherm and electrical resistance measurement methods as a point-by-point measurement of wood moisture. Passive sensors, on the other hand, operate without a supply voltage and use the energy in the environment, e.g., of the reader. Passive sensors include some radio frequency identification (RFID) tags.

3 Planning of the monitoring and data transfer

At the beginning, the choice of the measured quantity is a first important step next to the definition of the control points and their number. The density of measurement data must be defined individually from object to object or from control point to control point. Specialists in this field can assist and advice in deciding on a suitable system.

The installation of measurement sensors enables the acquisition of measurement data at defined intervals. Data can be transmitted from individual measuring points, e.g., by WLAN, LoRaWan or LPWan to a central module (gateway) and further to a WebPortal, as shown in Figure 2. If the measurement data are stored on a WebPortal, they can be viewed in quasi real time, e.g., from the workplace, and are available worldwide. The server can evaluate the measurement data and trigger warnings or an alarm. Storage and evaluation of the measurement data can also take place directly on the gateway or other measurement/storage units and release warnings or alarms (e.g., via SMS). After commissioning, these systems operate autonomously.

The various components (measuring points, measuring device, gateway and user interface) form the monitoring system. Battery-powered systems can operate maintenance-free for up to several years, depending on the system and the number of measuring points.

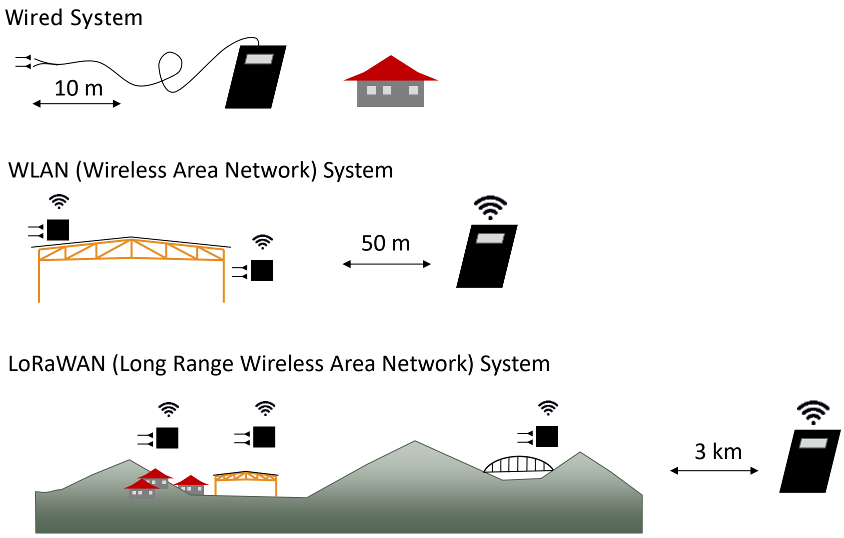

Figure 2: Overview of monitoring system's data management, Franke et al. (2022)

4 Conclusion and recommendations

Wood is a living and recognized construction material for the realization of taller timber buildings. However, wood is also a hygroscopic material and can absorb or release moisture from the surrounding climate. The so-called wood moisture content (MC) influences the material strengths and stiffnesses as well as the long-term load-bearing behavior. For this reason, continuous monitoring of wood moisture content is a suitable early warning system to increase the quality of wood structures in the future in a pioneering way and to detect changes in time.

The control points in the monitoring should be placed in possible danger zones/hot spots. These can include support areas, penetrations, pipe channels or where water is present, like in bathrooms. The various point and area methods presented are suitable for measuring wood moisture content. For the planning, implementation and evaluation of a monitoring system, the number of measuring points, the accuracy and the data storage/transmission should always be defined with a view to the objective. At this stage, an exchange with appropriate subject matter experts can provide positive support.

WG4.SG4.02

Monitoring of Wood Moisture Content in Timber Structures by Electrical Resistance and the Sorption Methods: Current Challenges

Philippe Grönquist, University of Stuttgart (Germany), **Nina Flexeder**, Technical University of Munich (Germany), **Bettina Franke**, Bern University of Applied Sciences (Switzerland), **Steffen Franke,** Bern University of Applied Sciences, (Switzerland)

1 Introduction

The moisture content (MC) in timber structures follows relative humidity and temperature variations due to seasonal climate and building use. It considerably influences the physical properties of wood below the fiber saturation point. The MC's influence on the mechanical/structural properties of wood and engineered wood products is particularly relevant in the context of current research on tall timber buildings. Whether a timber building is subject to outdoor weather exposure during its construction phase (Kordziel et al. 2019), or to strong indoor climate variations during service life, the MC is of central interest. Besides, it can serve as an important indicator of condition of sensitive components, e.g., where the wood is potentially exposed to leakage or condensation water, i.e. above fiber saturation point.

Although being the most accurate method to obtain the moisture MC of wood, which is formally defined as mass of water per mass of dry wood in %, the so-called oven-dry or gravimetric method (EN 13183-1, 2002) is considered destructive and not practical for monitoring applications. The non-destructive determination of MC is a well-established subject (Palma & Steiger 2020), especially for the discrete measurement with handheld meters. For monitoring, i.e. the permanent and continuous measurement of the MC of structures, several methods are available or under development. A distinction is made between pure leakage detection at timber elements and the determination of MC and moisture gradients in the component cross-section. For the latter, a sub-distinction can be made between single-point or laminar systems. Single-point systems can be used for the monitoring of small critical areas, and consists of the electrical resistance method (ERM) and the sorption method (SM). Besides, also capacitive methods are being developed for monitoring purposes, e.g. by RFID tag (Müller et al., 2022). Laminar systems encompass the measurement of electrical potential, e.g. by using sensor tapes or glass mats.

A current drawback of both the commonly used ERM and SM is their relatively poor accuracy. E.g., in the case of ERM according to Forsén & Tarvainen (2000), approximately ±1.5-2.5% MC. This typically represents uncertainties of up to 15-25% on a measured value of 10% MC, or of up to 30-50% on a value of 5% MC. For a better understanding of the in-situ structural as well as the long-term behaviour of timber components, e.g. using hygro-mechanical modelling (Jockwer et al. 2021), a higher accuracy of the methods would be highly desirable. Therefore, and as current and future tall timber buildings all represent potential future long-term monitoring projects, the challenges and need for future research of MC monitoring using ERM and SM will be addressed in this report.

2 Electrical resistance method (ERM)

The electrical resistance method (ERM) (EN 13183-2, 2002) is commonly used as a non-destructive method to estimate the MC of wood or engineered wood products in timber components. The method allows the measurement of MC in different depths from the surface, depending on electrode depth, see Figure 1a. The electrical resistance between two electrodes roughly ranges between 100 kΩ to 100 GΩ from the fiber saturation point to about 5% MC, respectively. The measured resistances and temperatures are converted to MC using linear calibration functions in a log(R) vs. log(MC) plot, see Figure 1b. These are typically obtained in steady-state conditions by fitting resistance data collected on wood samples equilibrated at different climates, and where the MC was determined by the oven-dry method (Grönquist et al., 2021; Schiere et al. 2021). After taking into account factors that may highly affect accuracy, such as orientation towards the wood fiber, type of electrodes, wood density, type of wood or engineered wood product (e.g. gluelines), temperature, applied voltage, and potential sources of electrical field interferences (Skaar, 1988), this method is claimed to be accurate up to ± 1 % MC (Dietsch et al., 2015), although other sources report lower accuracies of up to ±2.5% MC, even for laboratory conditions (Forsén & Tarvainen, 2000). Using repeated measurements between built-in electrodes over a longer time-span, the electrical resistance method has been adapted as a technique in long term monitoring campaigns, e.g. in Franke et al. (2015), Gamper et al. (2014), Brischke et al. (2008), Niklewski et al. (2017), Björngrim (2017), Li et al. (2018).

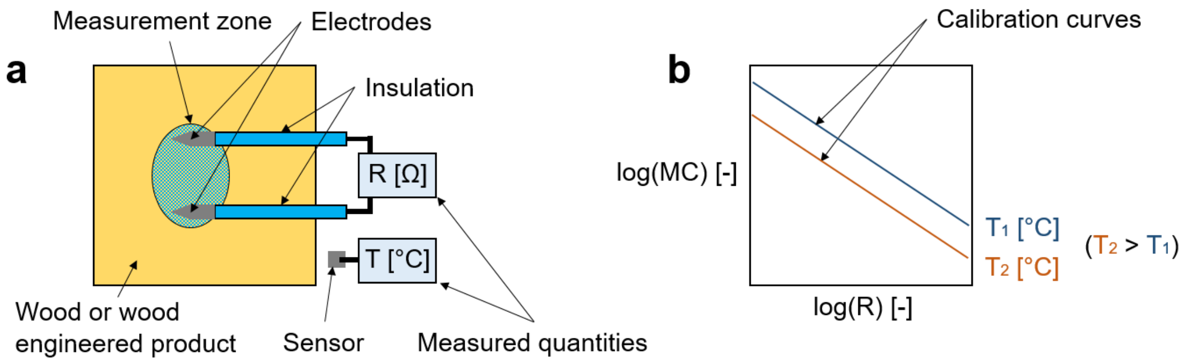

*Figure 1 Electrical resistance method (ERM): a: Setup of measurement (measured quantities: Resistance R, and Temperature T (at surface or close to electrodes)). b: Conversion to wood moisture content (MC) using steady-state-obtained calibration curves for different values of T, shown as linear functions log(R)=A-B*log(MC) in a log-log plot.*

3 Sorption method (SM)

Another method to monitor wood MC is the so-called sorption method (SM) (Dietsch et al. (2015), also referred to as sorption isotherm method, sorptive method, bore hole method (Li et al., 2018) or hygrometric method (Flexeder, 2022). Sorption isotherms are used to convert relative humidity (RH) and temperature (T) measured in a small cavity in the wood to a value of equilibrium MC (see Figure 2). Sorption isotherms are well known for common wood species and at various temperature levels. Examples were presented by Keylwerth & Noack (1964), Rijsdijk & Laming (1994) or De Backer et al. (2016). Various mathematical models on how to convert the RH and T values to MC exist (Avramidis, 1989). Some of them are presented in the current edition of the Wood Handbook (Simpson, 1973; Glass et al., 2014; Forest Products Laboratory, 2021). An example of long-term monitoring performed with the sorption method is that of the MC monitoring of timber bridges in Norway (Dyken & Kepp, 2010). The authors fit a second-order polynomial through measurements made in different RH and T (from -20 °C to 20 °C). The calculated fit relation allowed the determination of wood MC for Nordic pine (*Pinus sylvestris*). Melin et al. (2016) used the sorption method to monitor moisture content variations in wooden objects of cultural significance located in museums.

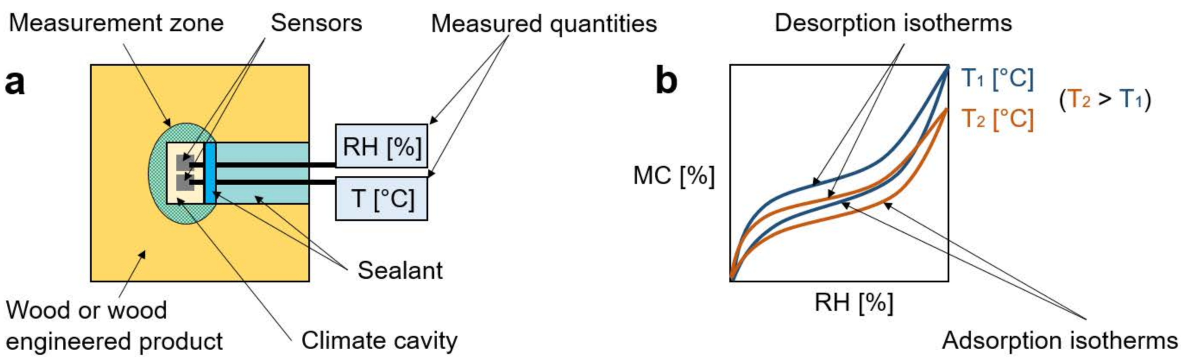

Figure 2 Sorption method (SM). a: Setup of measurement (measured quantities: Relative humidity RH, and Temperature T). b: Conversion to wood moisture content (MC) using steady-state-obtained adsorption and desorption isotherm curves for different values of T.

4 Comparison of ERM and SM

The choice on which method is to be applied depends largely on the environmental parameters and on available conversion parameters. Apart from that, acquisition equipment can also be important in the choice of the measuring method. A comparison of ERM and SM is given in Table 1 below.

Table 1 Comparison between ERM and SM for long-term MC monitoring.

	Electrical resistance method (ERM)	**Sorption method (SM)**
Required parameters	Electrical resistance (from 100 kΩ to 100 GΩ) and temperature.	Temperature and relative humidity.
Equipment	Electrodes (e.g. insulated nails or screws), cables, Ohmmeter, data logger, temperature sensor.	Humidity and temperature sensor in a sealed cavity, data logger.
Conversion to moisture content (MC)	Calibration curves from electrical resistance to MC and temperature compensation.	Sorption isotherms or Adsorption and desorption isotherms.
Advantages	Insensitive to material damage (e.g. cracks in wood)	Applicable in temperatures below 0°C. Applicable in salty, environments. Insensitive to grain orientation. Easy measurement of low MC
Disadvantages	Sensitive to material type, grain orientation, chemical composition of material, electrode type and spacing. Reliable in temperatures above 0°C only. Potential cracks and contact loss at electrodes in long-term measurements due to swelling/shrinkage around electrodes.	Sensitive to leakage of sealings (cracks). Sensor condensation or drift requiring recalibration. Limited to hygroscopic range of wood MC.
Accuracy	±1% MC up to ±2.5% MC for laboratory conditions.	±2.5% MC for laboratory conditions, due to uncertainty whether on adsorption or desorption isotherm, or in-between (scanning isotherm).

5 Current Challenges and need for future research

Melin et al. (2016) compared laboratory measurements with both ERM and SM on pine with the expected results by a Fickian model for moisture diffusion. They found very inconsistent results obtained by the ERM measurements. These investigations are similar to those by Flexeder et al. (2022), who also found distinctive differences between the values measured with ERM and SM in both laboratory experiments and field tests in an exterior cross-laminated timber wall. Therefore, for a future reliable use of both methods, it is worth investigating the potential influences causing the reported differences. Besides the already mentioned and inherent accuracy problem of both methods (see e.g. Table 1), some of the existing challenges that can be identified from current knowledge, and that might highly impact the accuracy of both methods in the context of long-term monitoring (i.e. field measurement conditions) are:

For both methods:

- The laboratory conditions for the determination of the calibration or sorption isotherm do not correspond to the real building service conditions. In particular, the influence of temperature gradients and moisture gradients in timber components can cause significant measurement errors (Fredriksson et al. 2020). Both calibration curve or sorption isotherm are determined and valid only under controlled steady-state conditions.
- The uncertainty of the influence of local material variations within the structure, which can significantly differ from material samples used during the calibration or determination of the sorption isotherm, will affect the accuracy of both methods.

For the ERM separately:

- Under temperature and moisture gradients, the electrical current will travel along the path of least resistance, i.e. will lead to a higher MC than is present on average in the measurement zone. In addition, the Temperature is not necessarily measured at the precise location of said path.
- The electrodes are typically made out of thermally conductive metal. Therefore, it is questionable whether the ERM is suitable for determining wood MC in timber components exposed to high fluctuating temperatures. E.g., daily temperature fluctuations may dictate a specific required measurement interval due to otherwise significant potential measurement errors (Flexeder et. al, 2022).
- Typical indoor climate conditions in tall timber buildings in Europe, especially in the (heated) winter season, will lead to relatively low MCs of the wood (e.g., < 8%), where the precision range of the ERM is inherently low due to the high resistances and small currents. These small currents can be highly sensitive to third party electro-magnetic fields origination from building use. Therefore, leading to further potential inaccuracy.

For the SM separately:

- It is not clear to what extent the sorption hysteresis can ever be realistically taken into account for a conversion of RH and T to MC. Or, whether an optimal strategy in order to minimize this inherent inaccuracy would consist in taking the mean value between adsorption and desorption curves.
- There is no consensus on the exact mathematical form to use for the sorption isotherm curves, as most of them wrongly claim to be physical-based but are in fact not (Zelinka et al. 2018).

All of the above mentioned points are in need of further investigation towards the quantification of their impact on the accuracy and reliability of (long-term) MC monitoring. At best, optimal solutions or strategies may be found in order to enable the accuracy of MC monitoring to be reduced at least to correspond to the inherent accuracy of both methods in laboratory conditions.

WG4.SG4.03

Full-area covering leakage and wetness monitoring on big timber structures using real time monitoring systems

Andreas Rödel, ProGeo Monitoring Systeme und Services GmbH & Co. KG (Germany)

1 Introduction

Malfunctions of the moisture protection, be it leakages in sealing systems, insufficient drying behavior of enclosed building moisture, moisture redistribution due to convective and/or diffusive transport processes or accidents of water-bearing piping systems, lead to serious, substance-destroying damage to timber structures after only a short period of time, if they are not detected in time and eliminated in a targeted manner, Kern (2016). The risks of damage induced by malfunctions in the moisture protection system rise sharply with the increasing size and complexity of the structure and the growing trend toward using flat roof surfaces as "living space" with greenery, rainwater retention or photovoltaic systems, since the possibility of visually inspecting the moisture protection system and the subsequent planned elimination of faults is increasingly being lost. The increasing use of water-bearing systems in buildings, whether for underfloor heating, in pre-wall installations or for floor-level showers, creates further risks of moisture within the building, which increase proportionally to the size of the living space and number of residential units, and thus with the volume of the building structure.

As a consequence, a concept for the early detection of water induced faults is needed, where such an approach only makes sense if it is proven in practice to have a high and long-term effectiveness with regard to response behavior and detection reliability of faults and if it is available to the owner or person responsible for the building over the entire service life of the building without requiring scientific expertise for operation or analysis, BBR (1995).

A particular challenge is that moisture protection defects, especially if they are caused by events that cannot be predicted in terms of location and time, e.g. mechanical damage to the waterproofing, leaks in the vapor barrier, failure of pipe connections, can only be detected with a high degree of reliability if the monitoring method used allows faulty conditions to be detected with obligatory certainty in a sufficiently short time, irrespective of the location of the occurrence in the structure Rödel (2021a, 2022, 2021b).

Two monitoring approaches, which are now used extensively and successfully in the long-term monitoring of timber constructions, will be presented in more detail below.

2 Full area waterproofing leak monitoring of flat roof structures

Flat roofs are predominantly sealed with membrane-type waterproofing to protect against precipitation water. The tightness of the waterproofing used corresponds to its electrical insulation resistance. If the waterproofing is free of faults, most of the waterproofing materials used represent a system with very high electrical resistance over its entire area. Damage to the seal, on the other hand, leads directly to a localized loss of the electrical insulation effect with the ingress of moisture at the point of damage. These relationships are utilized for full-area measurement-based leak monitoring and localization of sealing damages. The method is also referred to as electro-resistive leakage monitoring.

An electrically conductive contact layer, usually in the form of glass non-woven, is arranged over the entire area between the thermal insulation and the waterproofing membrane in conjunction with a matrix of measuring nodes, usually with a grid spacing of 3 m. The measuring nodes contact the contact layer and, in conjunction with a measuring and evaluation unit belonging to the system, enable the location-related measurement of the electrical potential distribution in the contact layer, which results when a measuring voltage is applied to the wet outer side of the membrane via counter-electrodes arranged on the seal. If the membrane is intact, the result is a uniform electrical potential distribution with only a small spread of the measured values. Leakages in the membrane, on the other hand, lead to a locally strongly increased spatial potential distribution, regardless of where they occur in the seal. The maximum of this distribution, calculated based on the measured values and known measuring node positions, indicates the location of the leakage Rödel (2021b).

The principal function of the method and an example of a detected leak are shown in Figures 1 to 4.

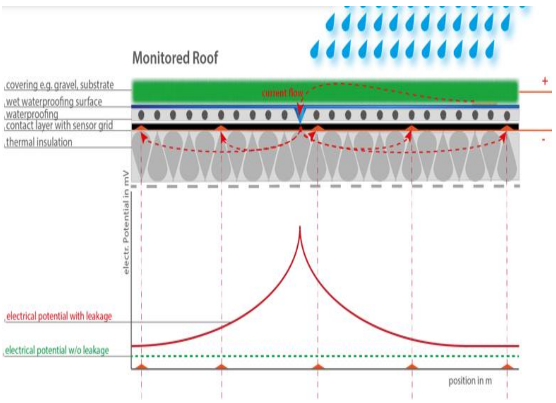

Figure 1 - smartex® mx functional principle

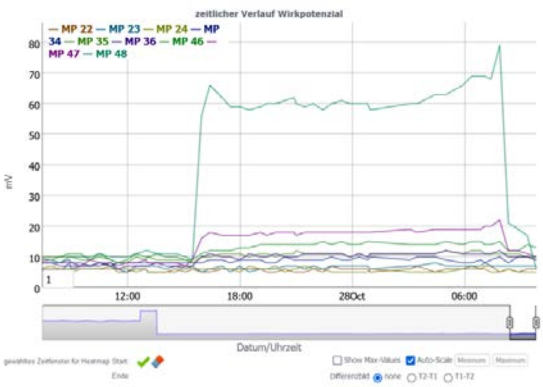

Figure 2 - timeline of measured data w/wo leak

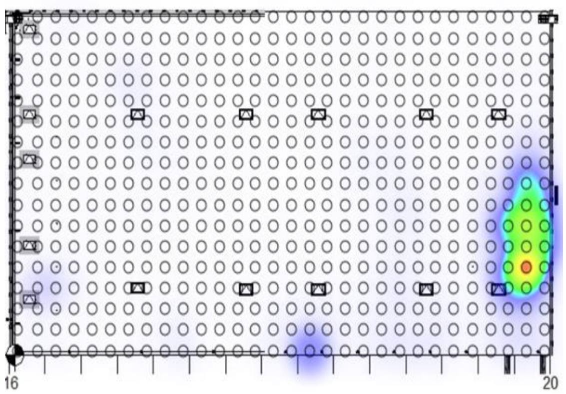

Figure 3 - spatial distribution of measured data with leak

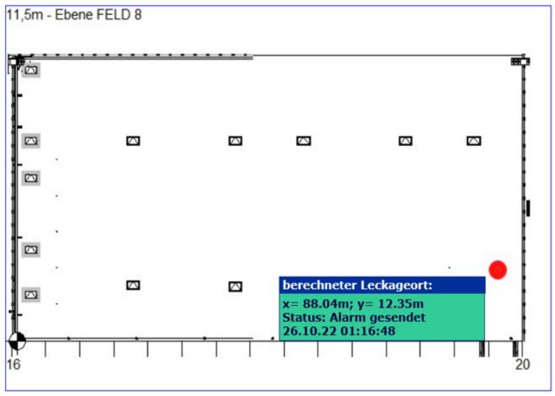

Figure 4 - calculated leak position, roof size appr. 6.000 m²

By automatically evaluating the measurement data obtained at short intervals, usually in conjunction with storage of the data at the central database server of a web-based monitoring portal, sealing leaks can be detected with the method practically in real time at the time of occurrence, and located with high accuracy, often in the range of a few decimeters. Comprehensive portal software is available for evaluations and reports. Alarm and status messages are sent by the system via email and/or text messages. Connections to local building automation systems are possible. The system can be extended to further measurement data acquisition, like wood moisture, temperature, humidity, water backwater or snow load.

Advantages of the method are:

- full-area leak monitoring of the waterproofing system based on an unambiguous measuring procedure that reacts immediately to faulty conditions
- optional visualization of the relative wetness or moisture distribution in the roof structure
- high response sensitivity
- fully automatable and real-time capable
- restoration of the damage-free tightness condition can be observed directly from the measured data
- no active electronic components are used inside the roof structure

The system is supplied as a ready-to-install system to match the roof structure. The raw installation is carried out by the roofing contractor. The final assembly is done by the object electrician or manufacturer.

The system is suitable for roof areas from 200 m² to +30,000 m² and more. A version without automatic leak positioning is available for very small and small roofs. The method is used especially for buildings with a high risk profile in terms of undetected moisture damage and/or poor or insufficient possibility of visual or technical inspection of the waterproofing layer from the outside of the waterproofing, e.g. roof areas covered with greenery or with technical installations.

3 Full area wetness and moisture monitoring with sensor tapes

Areas within the structure that are not visible and sensitive to moisture and in which moisture and wetness can occur for reasons other than membrane leakage during the service life of the building, e.g. floor structures of bathrooms or pre-wall areas with water-bearing pipe installations, can also be monitored for faulty conditions on an areawide basis with the aid of sensor tapes. For this purpose, the installation scheme of the sensor tapes can be designed freely within wide limits, considering the structural situation as well as the expected propagation of occurring wetness, whereby a good adaptation of the detection reliability can be achieved by selecting the number, length and installation spacing. Particular attention should be paid to the question of which smallest, permanent wetness propagations on unprotected wooden components, e.g. drip points at pipe connections, must still be reliably detected in order to be able to reliably exclude relevant long-term damage to the wooden structure.

Sensor tapes are available in different widths and designs. They are manufactured ready for installation according to an installation plan, so that installation can also be carried out by non-electricians. The physical measuring principle is usually a measurement of changes in the ohmic resistance between contact wires arranged in the sensor bands or of changes in the capacitance of sensor wires arranged in the sensor bands.

The measurement and evaluation of the measurement data can be carried out by purely local data acquisition and evaluation units, with which the condition of the tapes is continuously monitored, usually without storage of the measured data, or in conjunction with a connection to a web-based monitoring portal, like electro-resistive leak monitoring. Due to the continuous measurement, even in the case of rapid wetness propagation inside the structure, the starting point of the wetness can usually be spatially determined by specifying which sensor is the first to be affected, although it is not possible to specify the exact position on the affected tape, Rödel (2020).

If sensor tapes are laid with their contact wires in direct contact with a wooden structure to be monitored, the resistance measured between the wires, as long as no free wetness or moisture film acts on the sensor tape, represents an integral measured value proportional to the wood moisture content close to the structure surface, which makes it possible to observe the wetting and drying processes of the wood component over time in a simple manner, at least qualitatively.

The functional principle of the method, examples of installed sensor tapes and an example of a detected leak are shown in Figure 5 to 8.

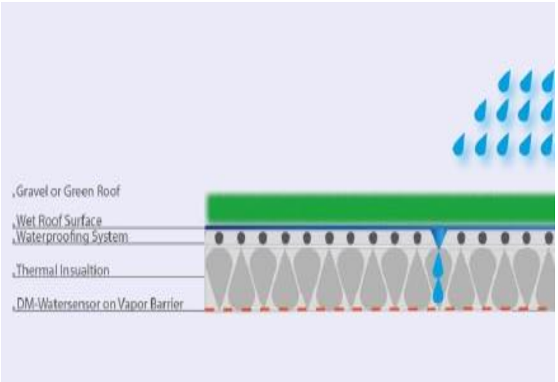

Figure 5 - functional principle smartex® dm

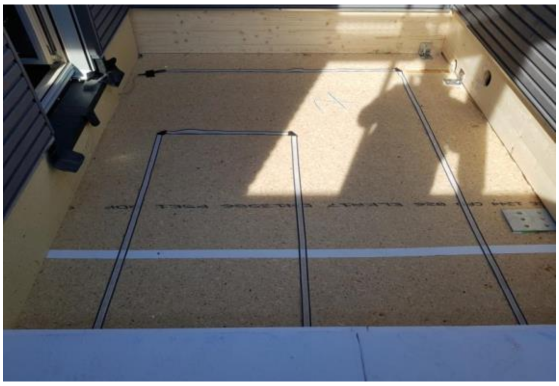

Figure 6 - wooden balcony structure with leak sensor tape

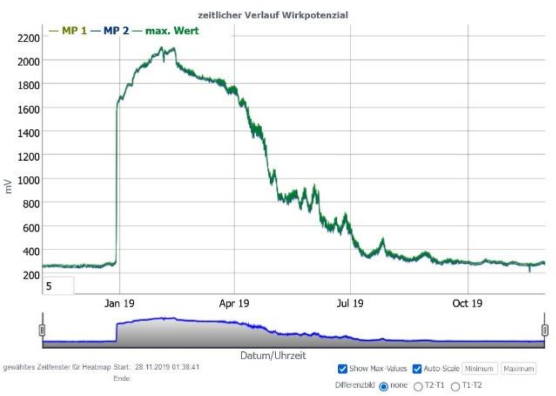

Figure 7 - timeline with water ingress and drying of structure

Figure 8 - leak sensor tape on wooden slab floor

A relatively new development are sensor tapes which, in addition to a change in resistance when directly exposed to moisture and humidity, also provide a change in electrical resistance when the relative humidity of the air inside the monitored component is exceeded. These tapes are particularly suitable for monitoring airtight compartments, where the relative humidity of the enclosed air increases in the event of moisture accumulation in the wooden structure or the present insulating materials.

Moisture and humidity monitoring with sensor tapes offers a simple way of automated detection of structural moisture protection failures with significantly higher detection reliability compared to point-type sensors. With the correct arrangement, areal monitoring can be achieved.

It should be noted that the monitoring methods described are instruments for the early detection and localization of defective conditions, enabling damage and changes to be identified at an early stage and their position in the structure to be localized to provide the prerequisites for early and scheduled repair. They do not replace diagnostic measuring methods for the exact determination of material parameters such as wood moisture or air water vapor content, which, however, are often not required in order to initiate suitable repair measures in good time.

WG4.SG4.04

Moisture exposure, damage mechanisms, and consequences – A risk-based perspective on timber products, construction activities, and building operation

Stephan Ott, Technical University of Munich (Germany), **Patrik Aondio,** Technical University of Munich (Germany)

1 Introduction

Apart from mechanical and fire performance there is another impact that threats all construction materials - that is moisture exposure and emerging damage mechanisms due to excess moisture conditions. The good message for timber as construction material, although it takes up moisture easily, it also releases it under suitable conditions. After the moisture uptake timber dries out and normally does not have any damages from becoming wet apart from optical changes e.g. stains. Also, the durability in terms of product life is not influenced negatively after a limited <u>time of wetness</u>, see Van Acker et al. (2014).

Historical examples of centuries-old wooden pile foundations in the medieval towns of Venice or Amsterdam indicate long-term durability. Traditional applications as façade cladding and roofing material in Scandinavia or Alpine regions demonstrate high resistance even to changing moisture under harsh exterior climate conditions. Also in non-constructional use, wood shows considerable resistance to moisture, as its use in water pipes or barrels demonstrates this robust material behaviour quite well.

Weather <u>exposure</u>, water <u>penetration</u>, and moisture-driven <u>damage mechanisms</u> in building materials are associated with exceeding moisture conditions of each construction material. Moisture exposure is found at foundations, continues throughout the entire building envelope and also occurs in the interior during use of buildings. Exceeding moisture conditions occur at various occasions and time spans, in the material during production, during transport, storage and installation at the construction site, or from unexpected leakage events during building operation, where it can exert its damaging effect.

1 Moisture impact on tall timber buildings

1.1 Moisture exposure scenarios / situations

When a timber building is constructed and operated, there are several times when the moisture content of the wood should be looked at more closely.

An initial consideration of the wood moisture content must be made at the time of production. The timber intended for processing should have an appropriate moisture content for the subsequent installation condition. For semi-finished or finished elements, the period between completion in the factory, installation on the construction site and completion of the building envelope is critical. As a general rule, these sensitive components, where connection or joining points have no moisture protection whatsoever, are packed in foils and stored temporarily. If the intermediate storage is not carried out properly, moisture damage can occur even before transport to the construction site. Another critical period is the transport to the construction site. During transport, elements must be appropriately protected and, if necessary, air-conditioned if they are particularly sensitive to moisture, such as stair components or shell components that are milled in three dimensions and require a high degree of dimensional stability or precision for installation. This is particularly important for transports with shipping containers.

The moisture effects mentioned so far are usually well known to the companies working in these areas and are complied with according to experience.

Most of the damage we know of is caused by improper storage of timber products on the construction site. This includes the failure to cover delivered timber products, but also the lack of moisture protection during the construction of the overall structure. In many cases, the planning of the construction process as well as the planning of the construction stages play an important role. If construction steps are chosen too large, it is hardly possible for craftsmen to react to rain events at short notice. In addition to rain events, the timing of the commissioning of the building services plays an important role. Damage can be caused by leaking pipes, but also by excessive heating and the associated shrinkage events.

With any unintentional moisture entry, it is important that it is detected as quickly as possible. The type of construction plays an important role here. For example, water penetration on a cross laminated timber ceiling is detected much later than on a beam ceiling. Due to the closed surface of the cross laminated timber ceiling, the water sometimes remains on it for a very long time and can lead to the growth of wood-destroying fungi, see Ott & Aondio (2020). In addition, water can penetrate into deeper layers in cross-laminated timber elements that are not glued to the narrow sides and lead to "hidden" fungal growth, as the fungus forms its own microclimate (moisture trapping). In contrary, water ingress is detected much earlier in timber beam ceilings or board stack ceilings, as the water finds a direct path through the construction. In general, wood and wood-based materials are relatively resistant to short periods of moisture penetration; only longer-lasting moisture penetration and trapped moisture, possibly in conjunction with uniform room temperatures or higher temperatures caused by heating distribution systems, are damaging. The relevant damage mechanisms are listed in Figure 2 and can be found in detail in the final report on the TallFacades research project. They occur with different moisture loads, i.e. amount of moisture and duration of exposure with corresponding boundary conditions (temperature, ventilation, etc.).

1.2 Water ingress and absorption

Wood basically has two ways of absorbing water. Water absorption can take place in liquid or gaseous form. It should be noted that the water absorption coefficient in the direction of the grain is considerably higher than perpendicular to the grain, see Figure 1.

When wood is installed outdoors, it is often exposed to the weather. Water should be drained off as quickly as possible and kept away from end-grain surfaces in particular. Since end-grain wood, due to its high capillary absorption capacity, absorbs water quickly and deeply into the cross-section and it takes a long time for this water to be released again, special care must be taken here. Moisture ingress in liquid form is often found at column bases, base areas of timber

	Water absorption coefficient Aw [kg/(m²·s^{0,5})]			
	Longitudinal	**Tangential**	**Radial**	**Literature**
	0,01670	0,00200	0,00300	(Sonderegger, 2011)
	0,01096	0,00154	0,00170	(Niemz, Sonderegger, Häring, Joščák, M. & Krackler, V. 2012)
	0,01350	0,00140	0,00141	(Niemz, Mannes, Koch& Herbers, 2010)
	0,02900	0,00290	0,00195	(Niemz, 2006) from (Niemz et al., 2010)
	0,02000	0,00186	0,00175	(Jakob, Niemz & Hurst, 2005) from (Niemz et al., 2010)
	0,01890	0,00400	0,00300	(Wang & Niemz, 2022) from (Niemz et al., 2010)
	0,01500	0,00375	0,00300	(Zillig, 2009)
ø	0,01772	0,00249	0,00226	
	Longitudinal	**Transversal**		
ø	0,01772	0,00238*		

*) transversal water absorption coefficient corresponds to the mean value of tangential and radial value

Figure 1: Water absorption coefficient values according to literature review.

walls, projecting beams and façade elements. But water can also be introduced in liquid form through leaking roof seals or installations.

For water to be introduced in vapour form, it requires a corresponding vapour pressure gradient. This can be caused by temperature differences. For example, water vapour diffuses from the inside to the outside in cold seasons, in the presence of a patchy or damaged vapour barrier. Alternatively, a diffusion flow from the outside to the inside can also take place if, for example, roofs are heated in summer and moisture is blocked if the vapour barrier is intact. Assessing the vapour transport of water requires a high level of knowledge of building physics and, if necessary, calculations or simulation. On the other hand, the entry of liquid water can usually be prevented by simple solutions, including craftsmanship and professional construction site management.

1.3 Damage mechanisms in mid-rise and tall timber buildings

With the introduction of innovative building products made of planar glued board lamellas, i.e. CLT, the restriction of load-bearing structures to linear and thus additively used load-bearing members was eliminated and gave tall timber buildings a boost. As a result, new, technically determined boundary conditions for moisture management in the interior of buildings have arisen. Due to the emergence of mass-timber, planar wall and floor components as in concrete construction, the integration of building services technology in timber construction has to take place differently than was the case traditionally. In addition, it can be observed that the damage to such planar building components is increasing, the detection of moisture damage is becoming more difficult and, ultimately, additional consequences and risks are not yet foreseeable. We propose to focus on the cause-effect relationship of increased water ingress to reveal the problem of moisture exposure in the interior of buildings with planar load-bearing structures, the damage mechanisms and direct consequences set in motion. These problem have to be tackled by adpated guidelines for MEP systems and for construction processes with specific planar construction products.

2 Risk management of moisture

2.1 Probabilistic method for improved moisture safety

With the increasing height of timber buildings, the challenge of creating moisture-proof conditions for the expected service life of building envelopes grows.

Compared to fire protection and structural requirements, the risk of failure due to moisture is dramatically underestimated in planning, construction, and quality management today. Although various statistics on structural damage clearly show that exceeding moisture content due to short-lived or insufficient component connections in the building envelope leads to reasonable economic damage, estimated at 3 - 5% of the total annual investment in new buildings in Europe. Experts assume that this proportion can be exceeded in the future by more insulated, more complex, and more vulnerable building envelopes. There are already basic and deterministic rules for the development of moisture-proof facades as well as for certain highly exposed (vulnerable detailing) with geometry changes such as window openings and several others. This approach does not consider the uncertainty of the composition of the construction component and execution of construction details and the variability of *Climate Exposure* (CE) as well as the *System Response* (SR) of a specific detail. Therefore, "semi-probabilistic safety concepts", as applied in static calculations, are necessary to avoid negative consequences of an improper reaction of the building envelope to moisture pollution.

The following Figure 2 shows the risk assessment model components and their relationship between the initial *System*, its *Exposure*, the probable *Failure Modes*, possible *Consequences* and applicable *Risk Reducing Measures (RRM)*. It also refers to the implementation of the model in simulation (*WUFI*) and calculus tools (*MATLAB*). The parameters of boundary conditions, *System* (S) description and *Failure Mode* (FM) limit values are filled with valid data for a specific case. Then moisture content in *Simulation Results* will be interpreted to *Consequences*, if RRM are added, the model must be rerun. Also, different designs can be compared to see which ones performs best. With *LCC* and *LCA* methods applied, its possible to find cost effective solutions, or options with lowest environmental impact.

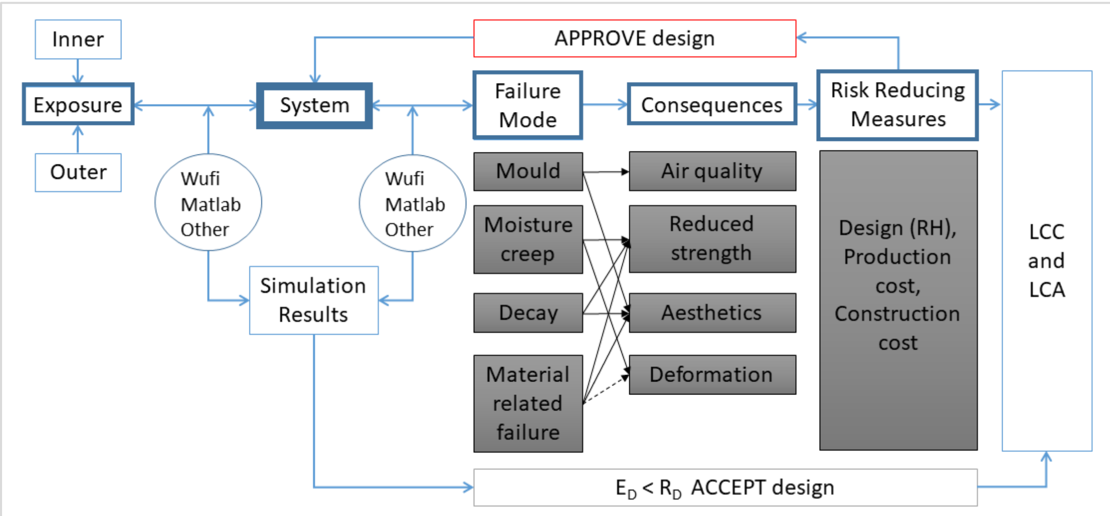

Figure 2: Risk assessment components to calculate the probability of failure. Consequences are matched with costs of repair. Further adjustment with risk reducing measures will show if additional measures are worthwhile.

2.2 Event tree analysis for detailing moisture sensitive connections

An event tree is usable as a 'reverse' consequence-based method to evaluate individual connections or joints of moisture risk areas, see Ott et al. (2018). The monetarisation of consequences demonstrated the relevance of moisture safety measures in order to avoid very high costs for timber construction companies. The event tree approach can be used for development of alternative joint solutions. The findings are relevant for construction companies due to the high monetary impact of possible moisture damages on envelopes of tall timber buildings.

2.3 Probabilistic moisture assessment of plain wall panels

Additional to the presented event-tree approach there is also a numerical tool developed based on hygrothermal simulation with commercial software (i.e. WUFI) that allows the FEM computation of one-dimensional component cross-sections of plain wall panels. The numerical tool is directly usable for prototype design and producing input for stochastic analysis, see the final report of the TallFacades research project from Tietze et al (2017).

3 Conclusions

Recommendation for the protection of wood against moisture-related damage, the current valid practice is to limit the allowable wood moisture content to *u = 18-20%* by mass. This boundary range is found in national regulations within Europe and also overseas. It limits the permanent moisture content of timber. The limit already takes into account a safety margin, since coniferous wood used in the building industry have moisture equilibrium of around *27%* by mass and the growth conditions for wood-destroying fungi only start beyond this limit. This safety margin is very generous with a *50%* surcharge.

WG4.SG4.05

Moisture management and monitoring during erection and service life of tall wood buildings

Mariapaola Riggio, Oregon State University (USA)

1 Introduction

Faced with timber products and construction systems that are growing in scale, spreading to new climate zones, and encompassing different construction practices, the mass timber building community increasingly needs information to understand the impacts of environmental exposure and the efficacy of existing moisture management practices.

Precipitation, ice dams and ground water from the soil are the main external moisture sources in a building, with precipitation being the most impactful source. Building height and shape affect the pattern of precipitation deposition and redistribution: tall mass timber buildings are subject to higher environmental loads, with higher impact of wind-driven rain on the upper stories and increased run-down water at the lower floors. Exposure of mass timber members during construction and the consequent wetting and moisture entrapment in an assembly can cause built-up moisture, which may have consequences also during the service life of the building. In buildings in service, water vapor is the principal indoor moisture source.

Several monitoring studies have provided insights on wetting, drying and durability performance of wall and floor assemblies in varying exposure conditions, and have also highlighted the potential benefits of developing more unified monitoring methods and data-driven approaches to moisture management. This paper summarizes major finding from these studies and highlights some research needs.

2 Current practice, challenges, and research needs

Figure 1 shows a general workflow for the hygrothermal monitoring of timber buildings, from the stage of data input (collection, processing, etc.) to the use of output information to inform various decision-making processes.

2.1 Defining the scope of moisture monitoring

The first step for the design of a moisture monitoring plan is the definition of the monitoring scopes. Generally, scopes of monitoring range from informing either immediate actions (i.e., damage assessment after a major event), or differed actions, for instance in case of doubts on the current serviceability or structural performance. Long-term monitoring data can be also used for service life planning, and cost-effective scheduling of inspections, maintenance, and repairs. Industry and academia are also interested in using monitoring data to validate new designs (Riggio and Dilmaghani, 2022; Schmidt et al., 2018).

Despite the availability of useful guides, such as the CLT Handbook chapters on “Building enclosure design for cross-laminated timber construction” (Karacabeyli and Cagnon, 2013 and 2019) European standards for moisture control (DIN EN 15228:2009) (SFS 5978) there are still many unanswered questions posed by the building community regarding moisture performance and management of mass timber buildings during construction. Some of these questions include criteria for monitoring wood moisture content during construction and analysis of site data. Several monitoring projects of mass timber buildings have tried to tackle this problem.

In addition, some projects include permanent sensor installations to record data during the life of the building, thus helping validate design decisions and determine the long-term performance of novel engineering systems. For instance, combined effects of mechanical loading and prolonged high moisture contents may trigger mechano-sorptive deformations, that can lead to creep and tension losses in pre-stressed or post-tensioned timber structures, as observed in post-tensioned timber frames (Granello et al. 2018) and rocking shear walls (He et al. 2022).

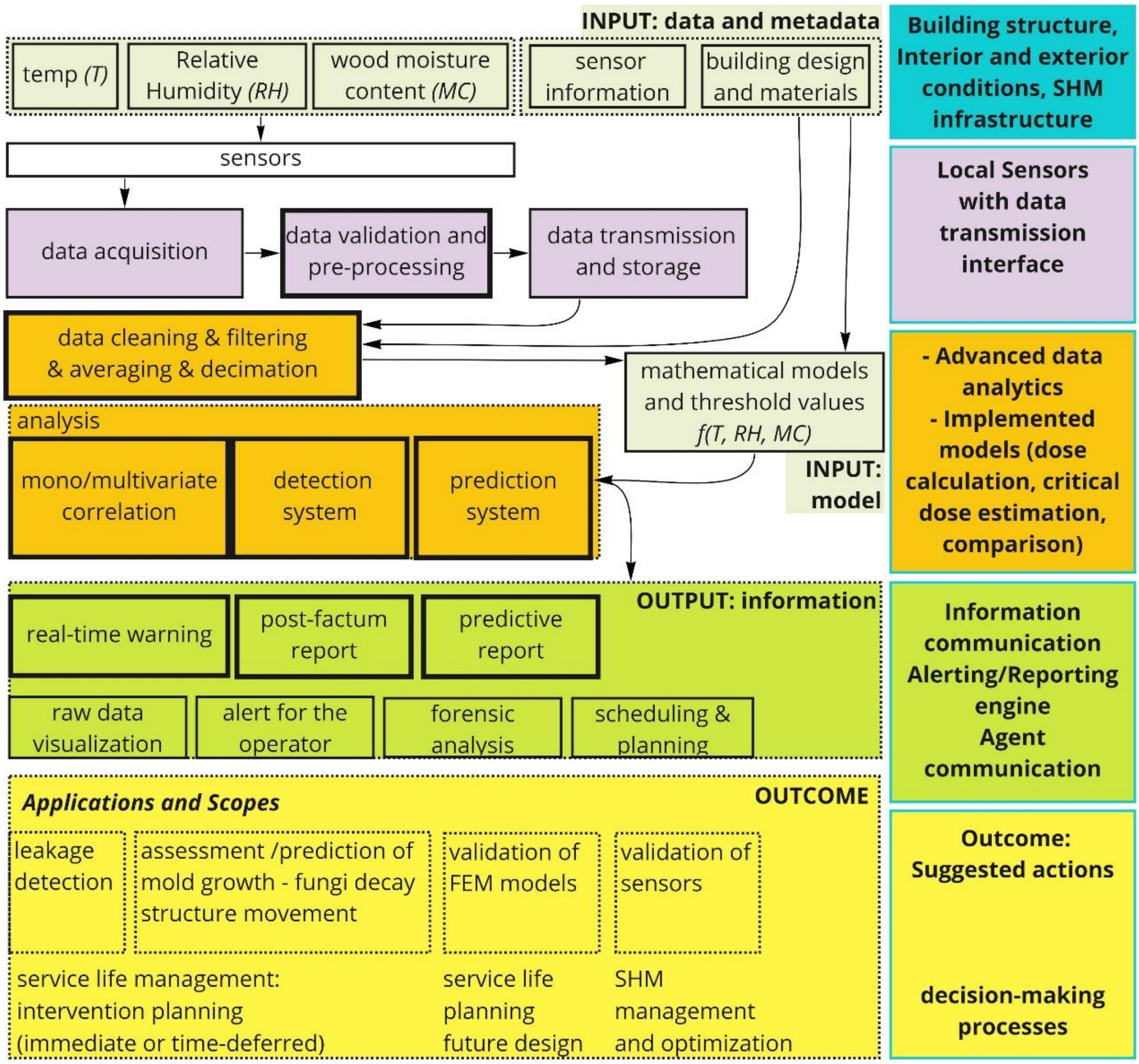

Figure 1 – Hygrothermal monitoring workflow (from Riggio et al. 2022)

2.2 Design and implementation of the monitoring system

Types of sensors

Environmental parameters, such as relative humidity (RH) and temperature (T) affect diffusion-driven moisture movement in wood. In addition, wood can absorb liquid water by gravity or capillary action. This second moisture transfer mechanism is faster than diffusion and is frequent during construction in the absence of effective deflection and drainage measures. Depending on the phenomena of interest and relevant observable parameters, different hygrothermal monitoring approaches can be used.

To monitor moisture content in wood, resistance-type moisture meters are the most commonly used devices. They are particularly recommended if measurements at different depths/laminas are desirable. (Baas et al, 2021) reported several factors affecting the quality of resistance meter data, which were identified in previous studies. Among these factors, there are: loss of contact of the electrodes with the wood during installation or in service (presence of checks or other discontinuities in the proximity of the probes); direct contact of sensors with water (rain, condensation, etc.); incorrect temperature calibrations (for instance, if temperature inside mass timber cores differs from surface temperature used for calibration); improper installation of sensors (e.g., position of pins with respect to the grain, damage of insulating coating during insertion, etc.); and electrical interferences.

Thermistors and RH gauges are employed to monitor building microclimates and can be used to indirectly estimate moisture content through the use of sorption isotherms (Glass and Zelinka, 2021). Despite the general reliability and ease of use of these sensors, authors have highlighted some aspects to consider when using RH and T data. These include: reaction time of moisture content changes due to diffusion in relation with changes of RH and T; reliability of interpolating internal temperature from surface measurements; and, weather exposure of gauges and effects on measurements.

Installation of sensors during the construction phase (or even before, at the manufacturer premises) can be problematic and requires special attention to avoid physical damage during construction activities and protect the monitoring system from environmental exposure. Authors have highlighted the need for more research to systematically elicit the influence that environmental factors have on hygrothermal monitoring systems and selection of the most appropriate type of installation depending on the application (Schmidt and Riggio, 2019). Also, it is to identify optimal tradeoffs between sensor redundancy and capital investment. Possible strategies include combination of different hygrothermal sensors that can communicate with each other to provide more complete and reliable information (Riggio et al. 2022), and optimize sampling criteria, i.e., strategic sensor placement.

<u>Sampling criteria</u>

Sensor placement should be optimized considering scope of monitoring (and related phenomena of interest) as well as sources of variability in hygrothermal monitoring data. Sources of variability include are attributable to environmental, design, construction, and material factors, for instance: construction schedules and sequencing; spatial orientation; variable exposure of different elements in a building to wind and solar radiation; assembly details, such as moisture trapping conditions, and low permeable assemblies; variability in the wood material, surface treatments, etc.

In reported monitoring projects criteria used for the placement of sensors considered: the anticipated vulnerability of a location to moisture ingress and/or trapping (during construction, and in service - within the building envelope, internal locations at risk of leaks from pipes, etc.); the need to use hygrothermal data for correlation with other parameters of interest (strains, displacements, etc.); economic, technological, and construction considerations.

<u>Data transmission and storage</u>

(Explained in “Methods for the monitoring of wood moisture content in taller timber buildings”.)

<u>Data processing</u>

Temperature and RH data are generally used with minimal processing. If multiple sensors are used, the measurements in nearby/ comparable locations can be averaged.

Simple moving averages are commonly applied to process MC data from resistance-type meters. However, there is not a common approach on the time period used for calculation (Dietsch et al. 2015; Riggio et al. 2019; Shmulsky and Jones, 2011). Statistical processing has been implemented in some cases to remove unreliable data (Niklewski et al. 2018, Baas et al. 2020). Erroneous data omission (outside the measuring range) has been applied by Baas et al. 2020, to improve data readability and reliability.

There is a need to standardize procedures for post-processing of MC data to deliver clear and useful information to decision-makers.

2.3 Use of data to support decision making processes

The most common practice for hygrothermal monitoring of timber structures is to access and visualize sensor data collected from individual locations in a building and, by means of expert evaluations, identify areas of concern, i.e., where data reach values above acceptable thresholds. Some commercial monitoring systems allow setting of alarms triggered when those thresholds are reached. However, data outside the sensor measuring range or superimposed environmental effects (for instance, caused by condensation) may cause problems in the readings, and result in undue alarm events. On the other hand, some areas of concern may not be captured by sensor readings, unless those are analysed holistically. In fact, to evaluate the risk associated with high moisture conditions it is necessary to consider, in addition to SHM data, various factors affecting the local hygrothermal conditions, such as local microclimates, assembly details and material features. This detailed spatial and material data needs to be associated with monitoring data to support accurate decision-making processes.

In Baas et al. 2020, a data platform was implemented to provide some analytical tools to the end-user. For instance, it offered the option to identify effects of specific construction events in the temporal data sequences to evaluate the possible effects of such events on the monitored phenomena. The platform also integrated scaffolding tools to improve data interpretation. The study focused on a in mass timber building with CLT post-tensioned shear walls. Scaffolding included setting of condition warning limits, such as tension loss thresholds. Other warning limits included moisture thresholds indicative of decay risk and condition limits established in the US National Design Specification (NDS) for Wood Construction (NDS 2018). The data platform also incorporated various analytical equations to allow for data comparison and validation, such as comparison of equilibrium moisture content (EMC) with MC data using the Hailwood and Horrobin equation (Glass and Zelinka, 2021).

(Riggio et al. 2022) proposed the use of avatars, decentralized Web-based computing agents, to integrate data from a diversity of sensors ((for instance by filling data gaps or validating measurements considering additional sensor readings) and to improve data analysis to support decision-making processes (e.g., by integrating monitoring data over time into different hygrothermal parameters to apply alternative mould growth prediction models).

3 Conclusion

Monitoring of wood moisture is an important instrument to increase the durability of taller timber building. The basic methods are presented, and different measuring techniques are available on the market, who is constantly evolving. The monitoring equipment of a taller timber building should always be planned in consultation with experts, their experience should always be used. Despite several efforts, the potential of SHM projects of mass timber buildings is still underutilized. Some of the reported limitations are: the difficulty of data integration within a single project (e.g., different sensors, sampling criteria, types of signal, etc.) and among projects; lack of standardized approach for data post-processing; and the limited usability of predictive tools in a variety of contexts and full scale scenarios.

WG4.SG4.06

Approximation of the moisture content during service and erection time

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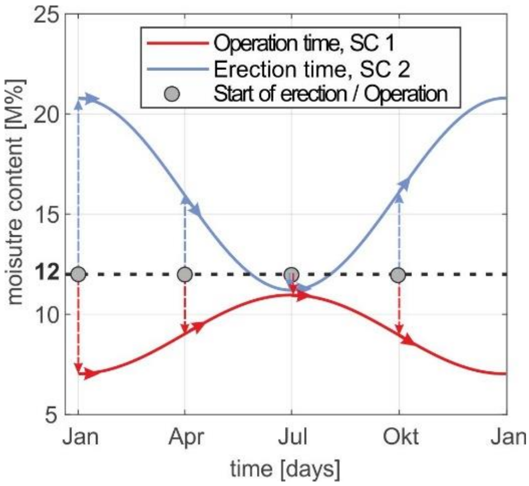
1 Introduction

For quality planning of timber buildings, the estimation of the expected wood moisture content especially during the construction process and in its use is still a challenge. The Eurocode 5, EN 1995-1-1:2010 is providing three Service Classes (SC) and would just account SC1 according to the use of the structural members as indoor use. However, the effects of, for example, moisture accumulation during the construction phase or the stresses that can be caused by the commissioning of the building are not shown. Assignment of the correct SC to a structure is one of the first important decisions a structural engineer needs to make when starting the design of a timber structure. In the following, further approaches and models are presented on how to calculate this impact in more detail.

2 Approximation of the moisture content using the ambient climate

2.1 Simplified climate exposure

A simplified climate model over the year could be applied for the approximation of the moisture content of timber members, the distribution over the cross-sections or the calculation of moisture induced stresses. Instead using the daily or seasonal changes, a model based on the cosines shape (Figure 1), or even a simple step model can be applied. For indoor climates according to Service Class 1 (SC1) respectively for outdoor climates but whether protected according to Service Class 2 (SC2) the mean equilibrium moisture content were set to 9 M% and 16 M% with an average variation of ± 3 M% and 5 M% respectively. While SC1 starts in dry conditions in wintertime, SC2 starts in wet conditions. The variations $\Delta u_{Surface}$ depend on the type of service and can individually derived from the service profiles developed in Franke et al. (2019). Specific service profiles like e.g. for sports halls, swimming pools, ice rinks, are evaluated according to moisture content and climate monitored under service conditions for at



$$u(t)_{SC1} = 9 + \frac{\Delta u_{Surface}}{2} \cos\left(2\pi \frac{t}{365} + \pi\right) \quad (1)$$

$$u(t)_{SC2} = 16 + \frac{\Delta u_{Surface}}{2} \cos\left(2\pi \frac{t}{365}\right) \quad (2)$$

where:

$$\Delta u_{Surface} = \Delta u_{15\,\text{mm}} \cdot r_u \quad (3)$$

t Time in Days, $t = 0 \triangleq 1^{st}$ of January

Figure 1 Cosinus shape model simplifying the yearly climate impact least one year. The developed envelopes can be used by practicing engineers and planners as support tool towards the design of a building. They also quickly allow to assess whether measured moisture contents are in ranges where the relative humidity is measured. Figure 2 shows, as example, the envelope development for sports halls.

2.2 Sample for the approximation of the moisture content during service and erection

The impact of the user/ambient climate and the meteorological whether on timber structures is calculated in example for a sports hall. First, the regulations regarding the EN 1995-1-1:2010 are applied and result in service class SC 1. Secondly, the approximation of the distribution of the moisture content over the cross-section using the service profile for sports halls as shown in Figure 2, (Franke et al. 2019) and the meteorological weather impact during erection time.

The result is a box of which the boundaries are set by relative humidity (horizontal axis) and measured moisture content (vertical axis). The sorption isotherm is plotted too (Simpson, 1973). Four different variables are obtained from the data:

- Average moisture content *øu*,
- the difference between minimum and maximum moisture content
  $\Delta u_{15mm} = \max(u_{15mm}) - \min(u_{15mm})$

Table 1 Calculation of expected moisture content for a sports hall

Situation: Sports hall located in Zürich Switzerland, Envelope closed and heated	
EN 1995-1-1:2010	Service Class 1: Temperature 20°C and rel. humidity ≤ 65%, $u \leq 12$ M%
Research approach	$u_{15\,mm} = 8.1 \pm \frac{1.83}{2}$ M%; $\Delta u_{Surface} = 1.83 \cdot 2.09 = 3.8$ M%
Location	Region Zurich, Switzerland: $16 \leq u \leq 18$ M%, $\Delta u = \pm 7$ M%
Begin of service time	Change from 12 M% to u (x M%) $u(\text{January } t=0)_{SC1} = 9 + \frac{3.8}{2}\cos\left(2\pi\frac{0}{365} + \pi\right) = 7$ M% $u(\text{July } t=180)_{SC1} = 9 + \frac{3.8}{2}\cos\left(2\pi\frac{180}{365} + \pi\right) = 11$ M%

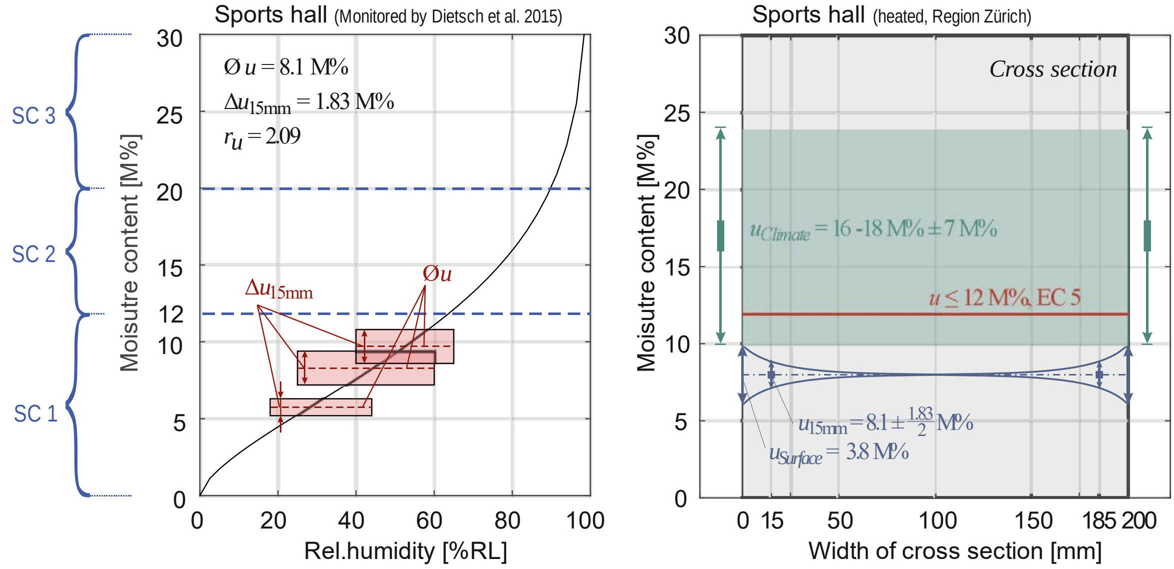


Figure 2 Envelope of sports halls (left) and visualization of expected moisture content over the cross sections (right)

- equilibrium moisture content at the surface $\Delta u_{surface}$= max($u_{surface}$) - min($u_{surface}$), and
- the ratio $r_{u,15mm} = \Delta u_{surface}/\Delta u_{15mm}$ between moisture content at the surface $\Delta u_{surface}$ and the amplitude at 15 mm depth Δu_{15mm}.

The EN 1995-1-1:2010 regulation is confirmed by the new research approach which gives further details about the distribution over the cross-section.

3 Impact of production and erection time on the moisture content

The season or period of construction affects the erected structures differently. As discussed already, spring and summers are generally dryer than autumns and winter. Figure 3 shows the moisture content variations, the dimensional changes, and the resulting moisture induced stresses in Service Classes (SC) 1 and 2 for structures erected either in January or June. The SC1 condition is plot in the right column and the SC2 condition in the left column. The moisture induced stresses were calculated using the numerical model by Schiere (2016).

Beams entering SC1 conditions suffer a large decrease of moisture content in winter (January). Straight out of the production facility at 12 M%, the beam is subjected to conditions that represent an equilibrium moisture content of 7 M%. Following the drying of the surface, tensile stresses at the surface will develop rapidly. Compression stresses in the cross section's midplane will develop only slowly.

In the case of the structural element entering the SC2 conditions in winter, the moisture content at the surface will increase after leaving the production facility. This results in tensile stresses

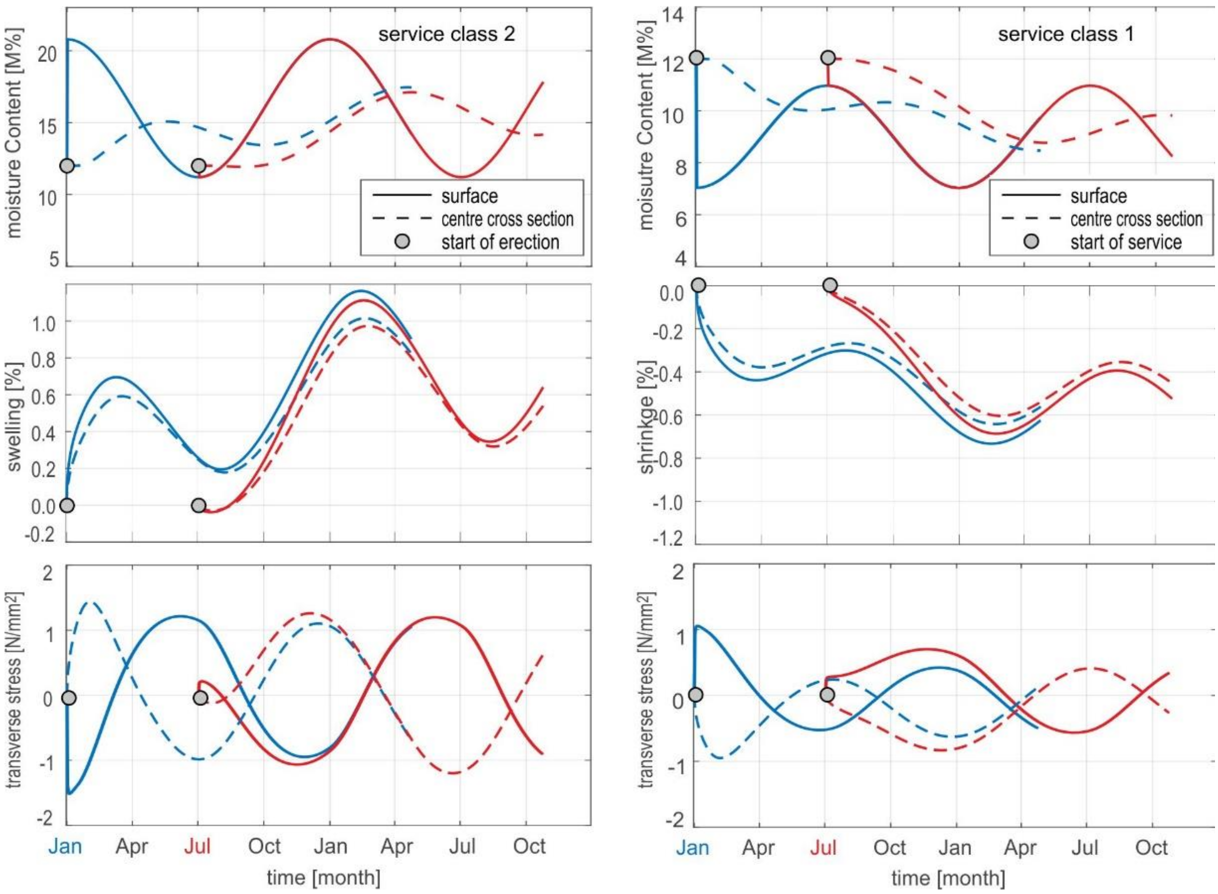


Figure 3 Results of the moisture content (left) and transverse stresses (right) for a cross section of 200/800 mm in Service Class 1 and 2 including seasonal changes of the ambient climate, developed by Franke et al. (2019)

in the midplane of the cross section which will gradually increase, and compression stresses at the surface of the cross-section which will increase rapidly. In this example, elements entering the construction site in summertime (July) are subjected to small moisture content variations and development of moisture induced stresses in SC1 and SC2.

It is noted that the duration of transfer from production facility to construction site is an idealized scenario: transfer of the building element to the construction site, installation on site (without any protection from sun or rain), closing of the building envelope and other climate scenarios until use are not included.

The following conclusions can be drawn from the diagrams in Figure 3.

- Moisture induced stresses at the surface react quickly to both drying or wetting loads in the surrounding climate.
- The smallest generated stresses due to seasonal variations in ambient climate are expected when structures are erected in summer period.
- Larger moisture induced stresses are expected when structures are erected during winter season.
- In erected structures the moisture induced stresses are expected to be lower in service class 1 operation than in Service Class 2 operation.
- The maximum tensile strength perpendicular to grain is expected to around 10 M%, which could be an explanation of the observed cracks perpendicular to the grain in dry structures.
- Moisture induced stresses in the midplane of the cross section take longer to develop. However, similar levels as achieved at the surface during drying are observed.
- Wood moisture content in the centre of cross sections of 200 mm require between one or two years to achieve the equilibrium moisture content due to their surrounding climates.
- Moisture diffusion in practice can be slower as expected from the simulations as slightly higher values were used than found in in-situ measurements.

4 Conclusion

Drying or wetting of timber elements also take place in insulated and heated buildings. The process of manufacturing, building period, until the intended operation during the «first winter» affects the moisture content distributions in the load bearing cross sections. It is believed to be best if timber elements are installed at equilibrium moisture content that is expected later in the finished building. Gentle pre-conditioning is to be recommended, especially where high-performance requirements are to be met. Deformations in connections must be concerned and to be limited for durability, refer to paper Frohnmüller (2022).

Protection from precipitation must be used during transport, storage, and erection. Timber elements must be covered continuously, therefore temporary roofs are recommended or efficient sequential erection with direct implementation of the finishing façade and/or roof as weather protection.

Wetting at the surface results in high stresses perpendicular to the grain which can lead to cracks later when surrounding relative humidities reduce again. Difference should be made between cracks which only reduce the visual appeal and those that have structural relevance. The use of surface treatments is to be checked individually, but too little experience has yet been gained on this matter.

WG4.SG4.07

Moisture induced stresses – numerical approaches and results

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1 Moisture induced stresses

Wood as a hygroscopic material adapts to variations of relative humidity and temperature of its surrounding environment: it either releases moisture in a drying process or adsorbs during a wetting process. The distribution of the moisture content across load bearing elements is normally non-uniform (Dietsch et al. 2015, Fortino et al. 2019, Franke et al. (2019)). The subsequent hygro-expansion and (constrained) swelling and shrinkage generates moisture induced stresses (MIS). These stresses can exceed the allowable strength perpendicular to the grain and generate cracks. The load-carrying capacity are reduced, and visible appeal of timber structures are affected. Structures are built throughout the year and building processes span multiple months until a building envelope is closed. Damage can be already initiated before the building is opened for its intended use.

2 Models, approaches and experiments

The moisture content in wood and resulting moisture induced stresses have been on the international research agenda for many years. The following of topics and publications are provided as examples of diversity and reflect only an initial selection:

- to wood drying and shape stability by Ormasson et al. (1999)
- deformation and fracture in wood-based panels after production by Gereke & Niemz (2010), Hassani et al. (2016)
- models to simulate moisture content distributions by Siau (1971), Crank (1975), Droin-Josserand et al. (1989), Wadsö (1994), Krabbenhoft und Damkilde (2004), Frandsen et al. (2007)
- models to simulate moisture induced stresses in glulam members by Ranta-Maunus (1990), Toratti (1992), Hanhijavirni (2000), Angst and Malo (2012), Angst-Nicollier (2012), Hassani (2015), Schiere (2016)
- models to simulate crack initiation and growth, Saft and Kaliske (2013), Franke and Quenneville (2011)
- experimental work to determine moisture induced stresses in glued laminated timber, Möhler and Steck (1980), Jönsson (2004), and Angst and Malo (2012)
- and quality assurance of timber structures, Häglund (2010), Fragiacomo et al. (2011), Müller and Franke (2015).

The variety of topics, results and insights are large, yet little of these results have found their way to the daily construction practice. It is imagined that this could be due to the complexity of the problem. The purpose of modelling is to isolate effects, investigate sensitivity of results to material parameters, and vary material properties, cross-section dimensions, drying loads etc. within an oversee-able amount of time and costs. Numerical modelling is an important tool for estimating the change in wood moisture content and its effects, and a few numerical results are shown below as examples.

3 Moisture content and deformation distribution over the small and large cross sections

Large cross sections become important to be used in taller timber buildings. They can be composed by gluing single glulam beams sideways onto each other forming a block glued glulam. The moisture content distribution and the deformation over smaller and larger cross sections are shown in Figure 1. The numerical simulation model by Schiere (2016) were used for the investigations. Smaller cross-sections respond faster to moisture content increases, due to the smaller amount of constraint during swelling and the faster increase in moisture. It takes a long time until the moisture content reaches equilibrium in the centre of the larger cross-section. Hence, building with wider cross-sections most likely results in smaller deformations. The plotted deformations are obtained from the maximum duration of the simulations. This was set to 120 days on the smaller cross-sections and 360 days on the large cross-sections.

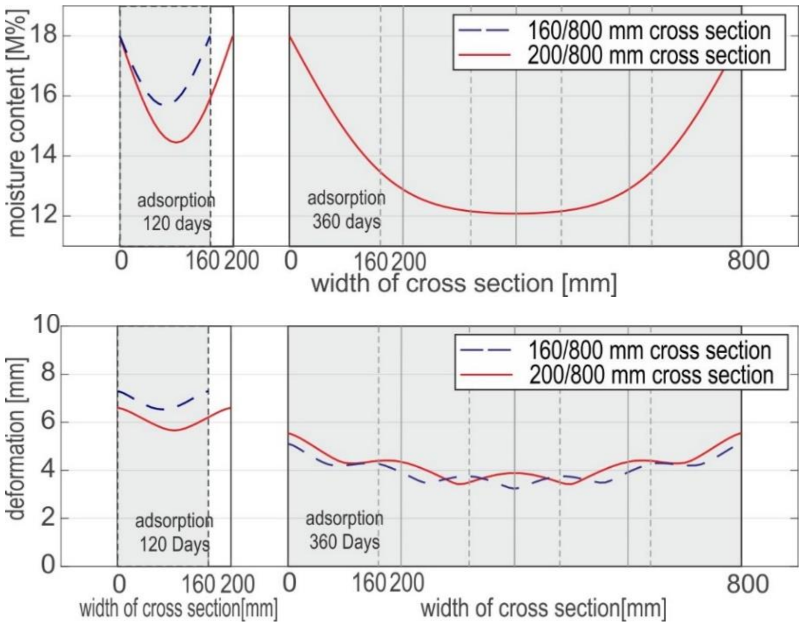

Figure 1 Distribution of the moisture content (left) and deformation (right) of timber beams of different widths subjected to step loads of 6 M% moisture content

4 Moisture induced stresses over the cross sections

4.1 Glulam cross sections

The effect of the aspect ratio on the stress levels achieved in the glulam cross-section was investigated by adding two boards on the layup for each simulation. The width of the glulam cross-section was maintained at 200 mm, whereas the depth was increased from 200 mm to 1000 mm. The aspect ratio does not affect the stresses developed at the surface much. The stresses in the midplane converge at an aspect ratio of 2 or higher, as shown in Figure 2.

4.2 Block glued glulam cross sections

The gluing of single beams sideways onto each other is expected to affect the moisture induced stresses in two ways.

- The ratio between the areas where the compressive stresses and the tensile stresses are present is different from those in slender beams. The tensile stresses are spread out over a larger portion of the cross section, resulting in smaller values.

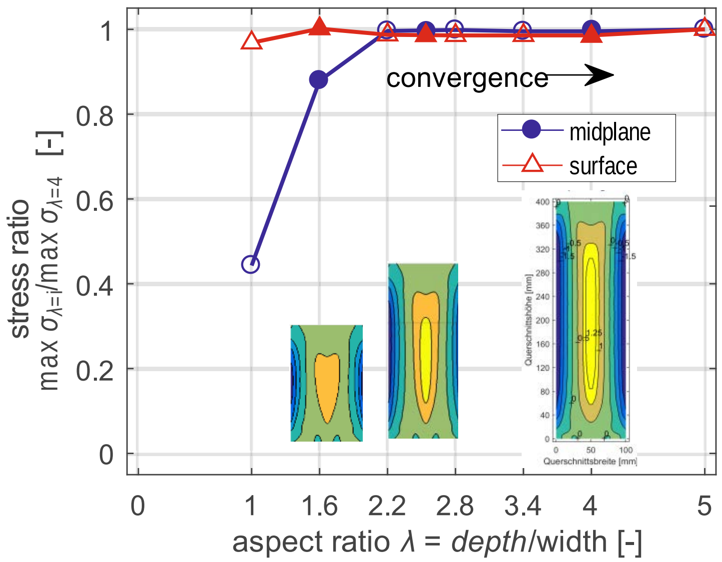

Figure 2 Effect of aspect ratio on stress levels on the surface and midplane of a glulam cross-section

- Since the cross section is not slender anymore, effects of aspect ratio also start playing a role and reduce the total amount of generated stresses in the cross section.

The calculated levels of moisture induced stresses in different widths of cross-sections is plotted in Figure 3. The stress distribution is plot at the point where the maximum tensile stress levels are achieved.

- Higher stress levels are found in block glulam beams with an uneven number of single beams when submitted to wetting process.
- In the block glulam beams with an even number of single beams, maximum stress levels are lower than in the uneven number of single beams.
- Converged stress levels remain around 0.5 MPa. The time needed for each of these beams to develop these stresses is different and all reach a maximum level long after the load was initially applied.

When the beams are subjected to drying loads, the width of the beam or the number of beams used does not affect the level of maximum tensile stress. These simply occur shortly after the driving load has changed at the surface. Therefore, at least some cracks perpendicular to the grain occur in almost all timber members in buildings.

To verify, if the aspect ratio affects the reduction of strains only, a simulation was done where the cross-section width and height were maintained constant, and the number of single beams was varied, Figure 4. Here too, the stress distribution perpendicular to the grain converges once four beams or more are used in the cross section. It is noted that the cross sections simulated here are not necessarily economical for use in practical production lines or construction.

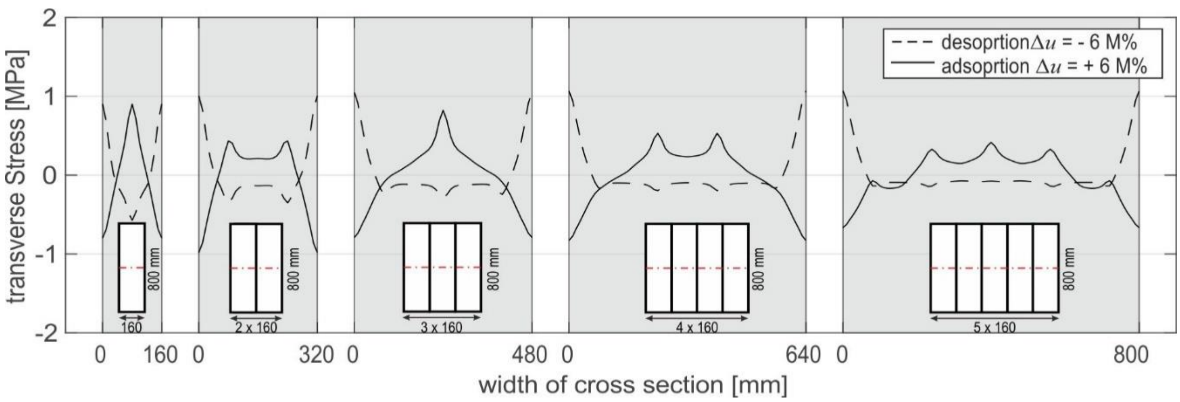

Figure 3 - Transverse stress depending on the width of the cross-section, step load of u = 12 ± 6 M%

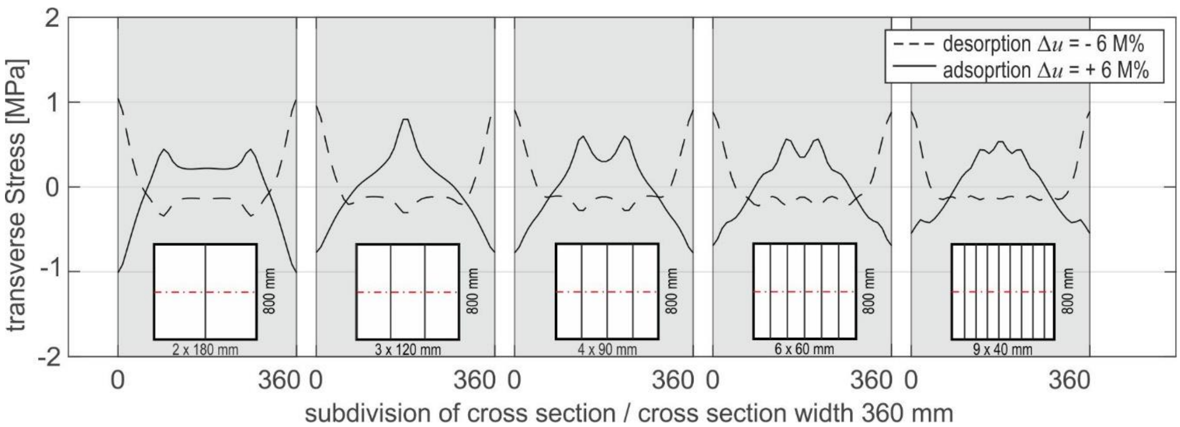

Figure 4 Transverse stresses with different number of beams used in the same cross section width, step load of u = 12 ± 6 M%

5 Conclusion

The moisture content is one of the important indicators for the quality assurance of timber structures. The moisture content variations lead to shrinkage and swelling of timber and change of material properties. Humid or dry surrounding climate leads to an adsorption or desorption respectively. The change of the moisture content leads not only to deformations but can also lead to moisture induced stresses in addition to the stresses caused by dead and service loads such that cracks can develop. Cracks at the surface reduce the visual appeal but can also lead to a reduction of load-bearing capacity.

The numerical simulations allowed insight in the dependency of moisture load and geometry on the generated moisture induced stresses. The results showed that moisture induced stresses depend on board layup, moisture load amplitude, geometry and beam slenderness, and sideway joining into block-glulam members. Drying loads almost instantly lead to high tensile stresses at the surface (and visible cracks), whereas wetting loads lead to gradual increase of tensile stresses in the midplane of the cross section. Cracks generated in the midplane are not visible but have however been observed during the demolition and inspection of timber structures. High moisture induced stress levels during wetting are already found in beams with slenderness ratios (height over width) of two and more. Drying stresses are not affected by the geometry. The use of block-gluing shows a positive effect on the development of stresses in the cross-section.

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