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

Sustainability and Durability of Taller Timber Buildings:

A State-of-the-Art Report

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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

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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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Table of Content

Foreword III
List of Authors IV

Part 1 Sustainability 1
WG4.SG1.01 Sustainability Assessment of Tall Timber Buildings 3
WG4.SG1.02 Environmental Impact Assessment of Timber in Construction in Europe 7
WG4.SG1.03 Potential of fast growing hardwoods for taller wood-based buildings 11

Part 2 Life Cycle Assessment 15
WG4.SG2.01 LCA of wood-based structures for taller timber buildings 17

Part 3 Durability 21
WG4.SG3.01 Durability of timber buildings – concepts, requirements and design 23
WG4.SG3.02 Durability of taller timber buildings – Wood coatings for exterior use 27
WG4.SG3.03 Assessing the durability of adhesively bonded timber-concrete composite structures 31
WG4.SG3.04 Seventh-year durability analysis of post-treated wood-based composites used in wooden buildings 35
WG4.SG3.05 Durability of timber connections 37
WG4.SG3.06 Holistic aspects and frameworks of lifecycle durability: climate change, sociotechnical robustness, and design for longitudinal learning 41

Part 4 Moisture Impact 45
WG4.SG4.01 Methods for the monitoring of wood moisture content in taller timber buildings 47
WG4.SG4.02 Monitoring of Wood Moisture Content in Timber Structures by Electrical Resistance and the Sorption Methods: Current Challenges 51
WG4.SG4.03 Full-area covering leakage and wetness monitoring on big timber structures using real time monitoring systems 55
WG4.SG4.04 Moisture exposure, damage mechanisms, and consequences – A risk-based perspective on timber products, construction activities, and building operation 59
WG4.SG4.05 Moisture management and monitoring during erection and service life of tall wood buildings 63
WG4.SG4.06 Approximation of the moisture content during service and erection time 67
WG4.SG4.07 Moisture induced stresses – numerical approaches and results 71

References (of all papers) 75

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).

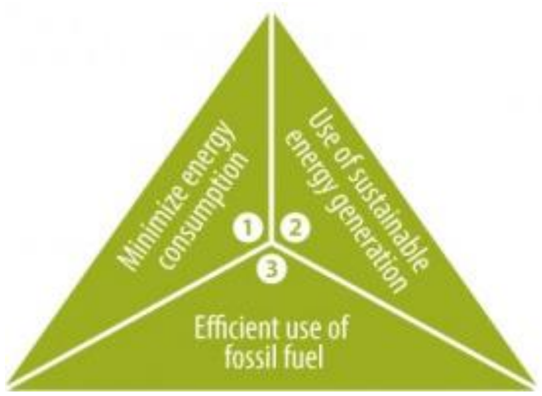

Figure 1a: Trias Energetica (Duijvestein, 2010)

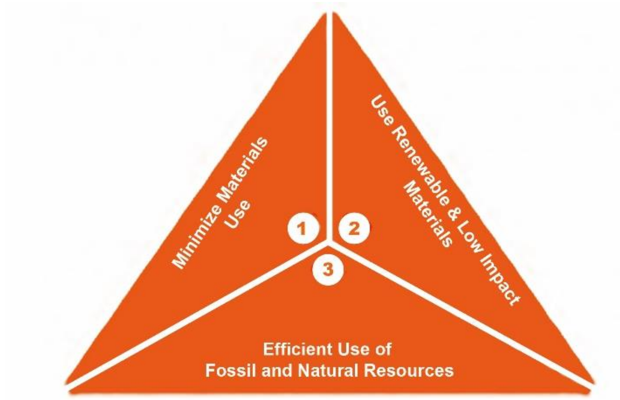

Figure 1a: Trias Materia (Duijvestein, 2010)

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.

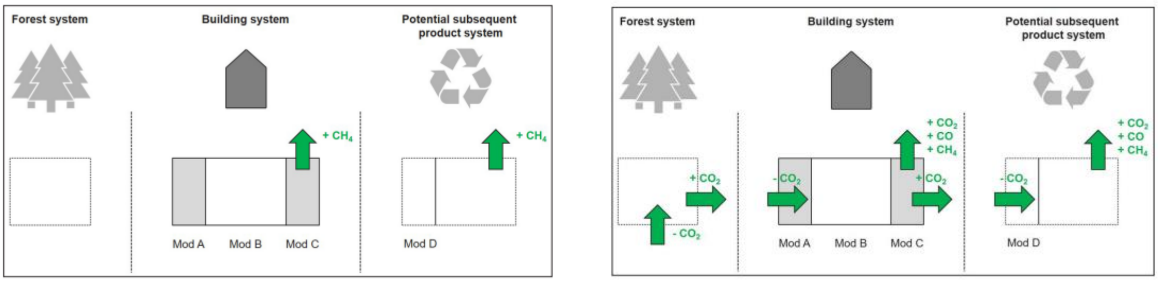

Figure 3a: The 0/0 approach to model biogenic carbon uptake and release. Dotted lines indicate the production systems that fall outside the building system boundaries. Figure 3b: The –1/+1 approach to model biogenic carbon uptake and release. Dotted lines indicate the production systems that fall outside 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.

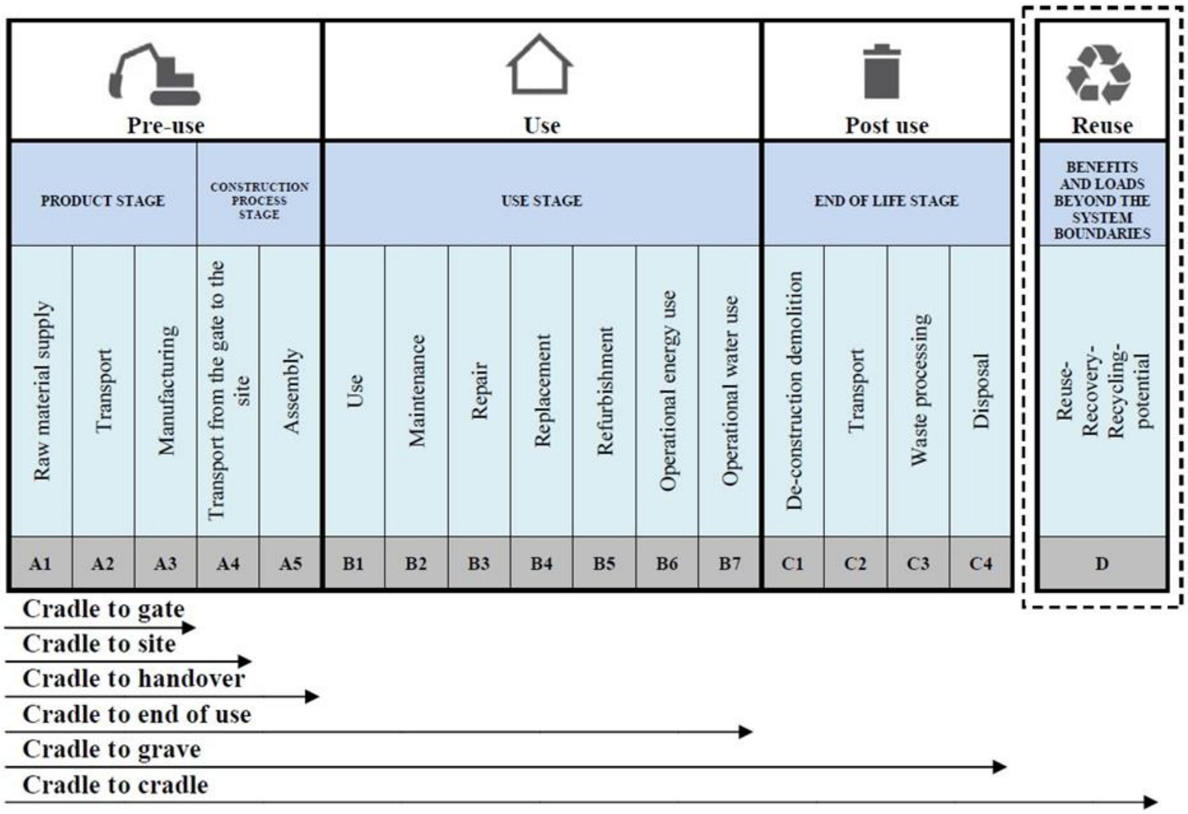

Figure 2: Description of the stages during the buildings' life, according to EN 15978.:2012, p.21

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.

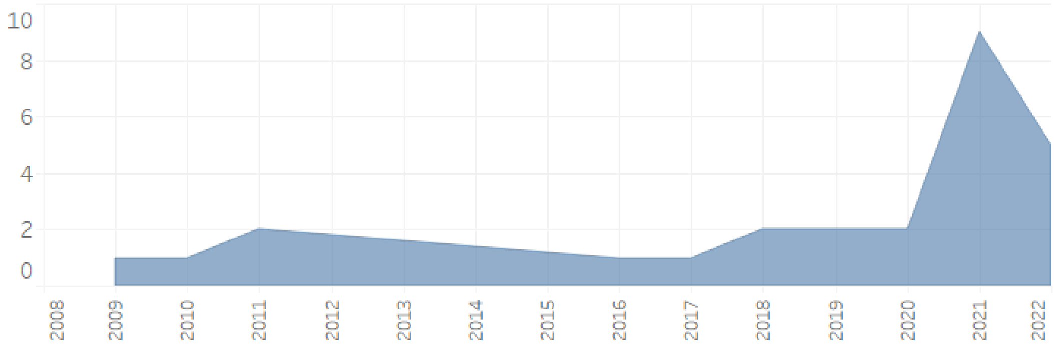

Figure 1: Count of publications by year

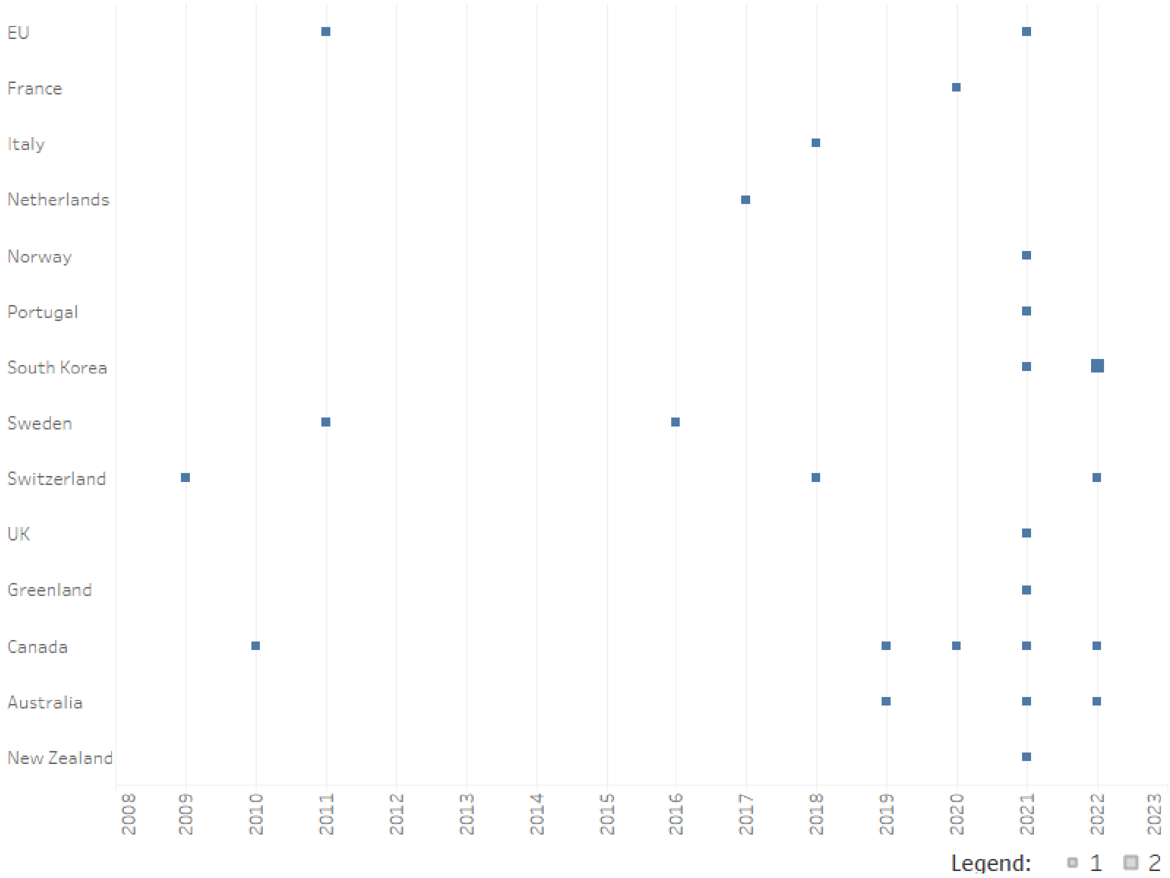

Figure 2: Count of publications by country, by year

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.

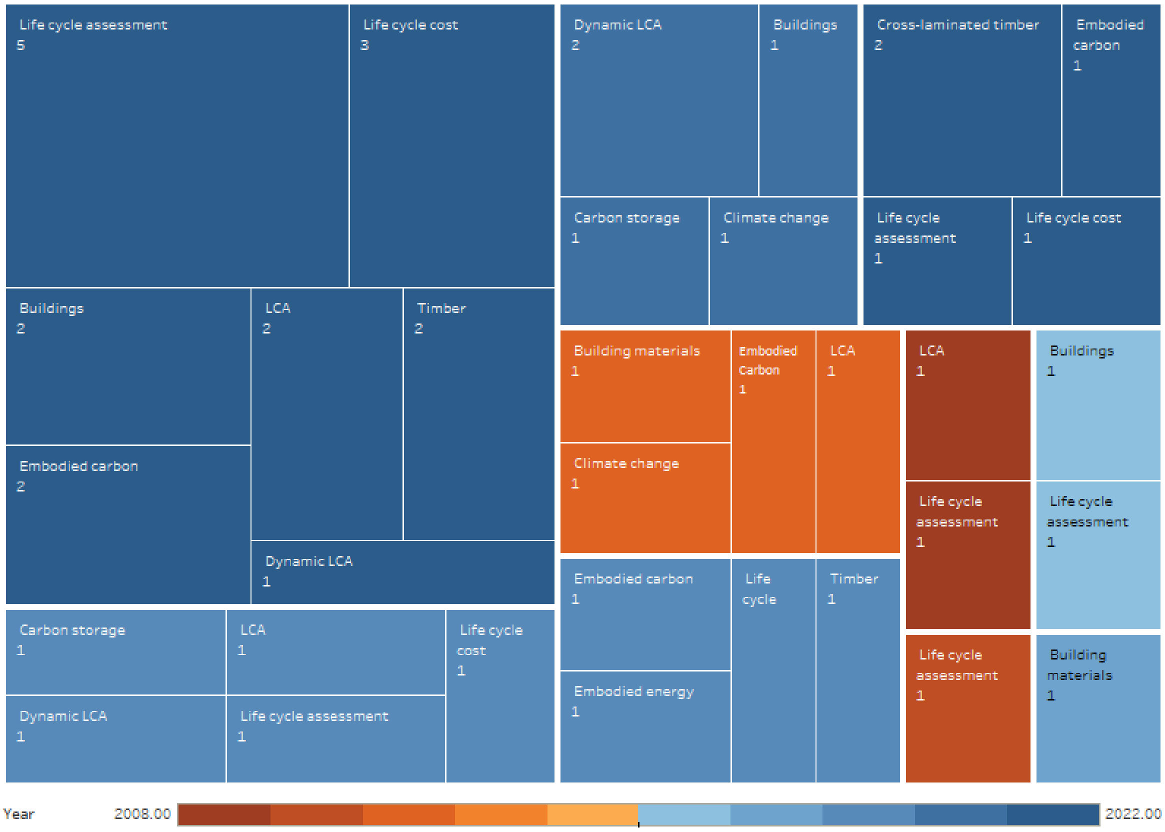

Figure 3: Publication keywords with total incidence > 1, by year.

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

Bettina Franke, Bern University of Applied Sciences, (Switzerland), **Steffen Franke**, Bern University of Applied Sciences, (Switzerland), **Jens Frohnmüller**, University of Kassel (Germany), **Annette Riel**, CREE Buildings (Austria)

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

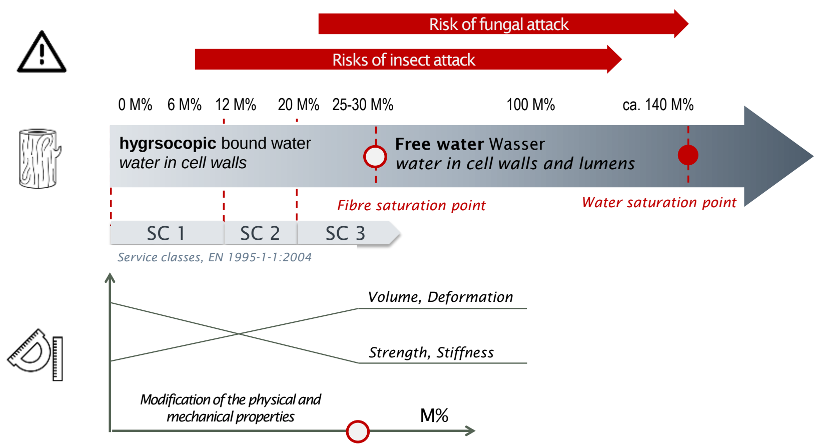

Figure 1: Presentation of the wood moisture content and its relationships to the moisture class, mechanical and physical properties and the hazards of the wood, Graphic developed by B. Franke

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

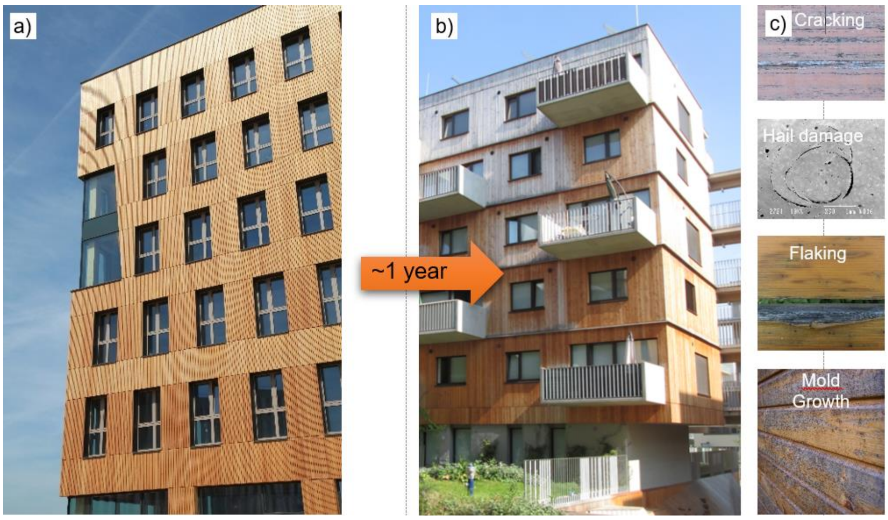

Figure 1: a) New facade of uncoated wood at HoHo in Vienna (2018), b): Seestadt Aspern, Vienna 2018, uncoated wood after one year of exposure with irregular discolouration; c) different coating damages: coatings are susceptible to damages and make frequent maintenance necessary, which is costly. Therefore, 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.

Figure 2: Silver grey semi-transparent coating that will be replaced by natural 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).

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.

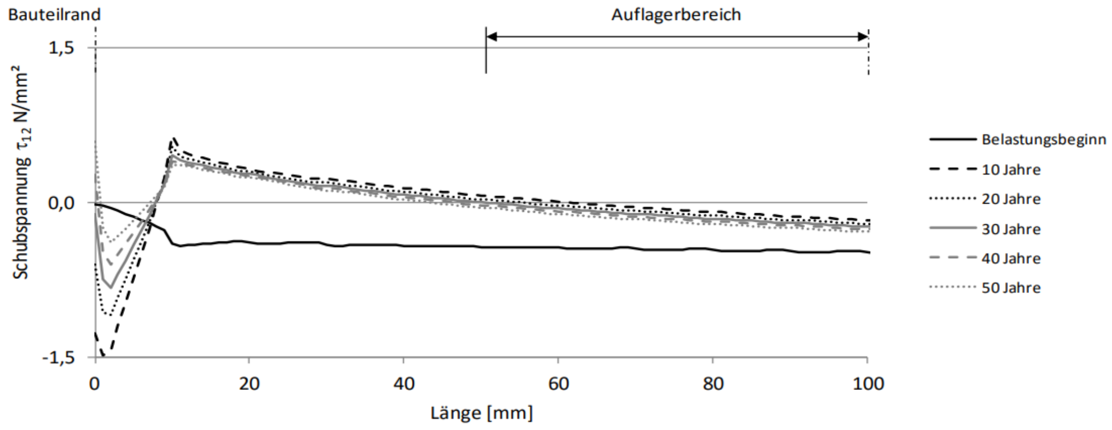

Figure 1: Development of the shear stress at the end of an adhesively-bonded timber-concrete composite beam with prefabricated concrete parts over 50 years. Source: Kühlborn (2016)

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.

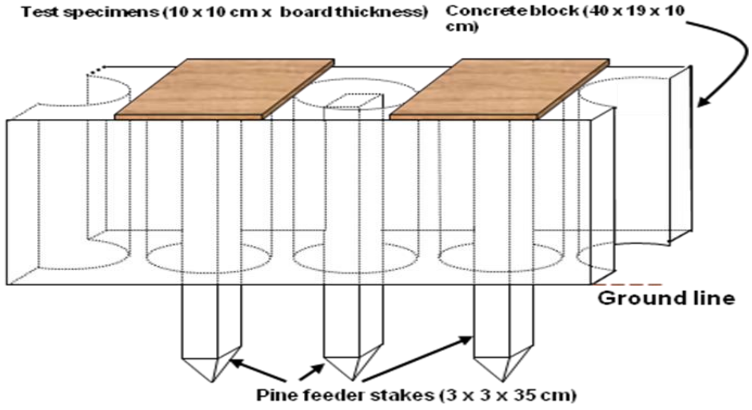

Figure 1. Installation details of specimens and feeder stakes in the Living Sphere Simulation Field (LSF) of RISH, Kagoshima, Japan

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.

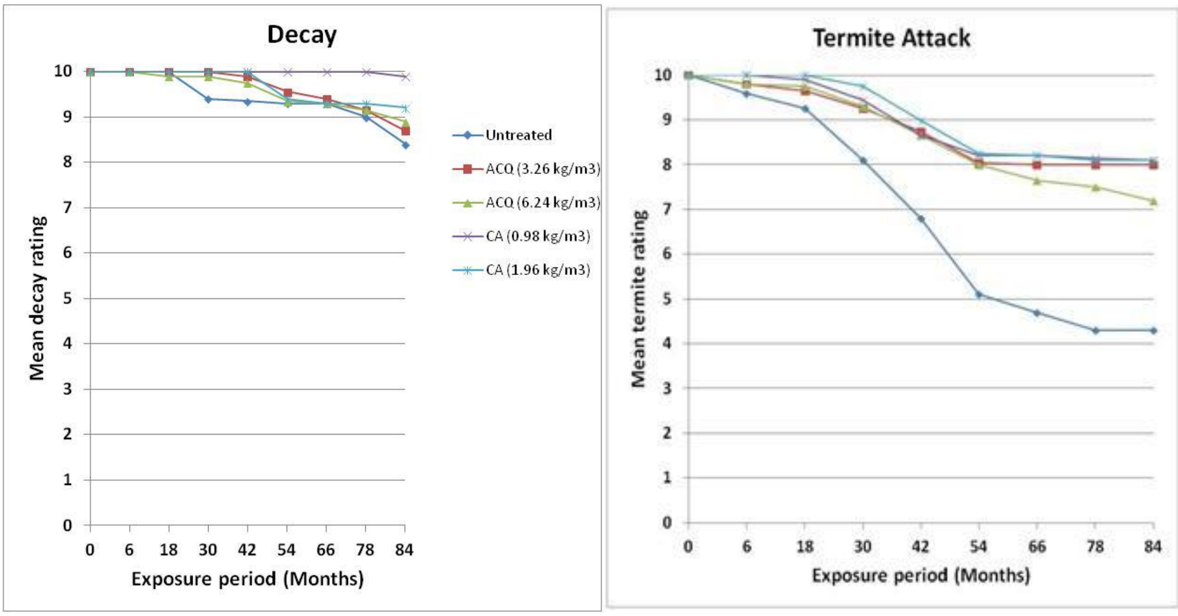

Figure 2: Progress in decay and termite attack for softwood plywood (SWP) during 84 months of exposure.

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.

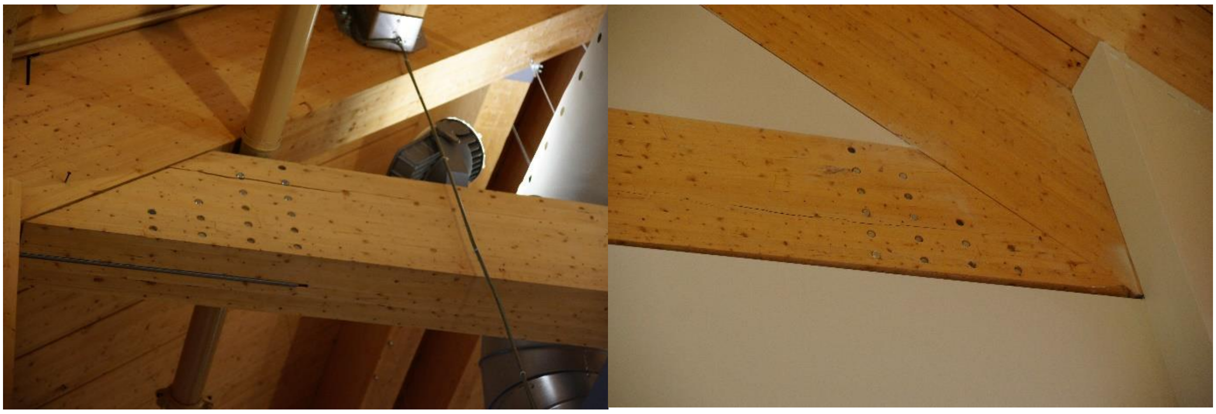

Figure 1: Cracks in the area of connections due to restraining effects

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

Katja Rodionova, Sitowise oy (Finland), **Jenna-Riia Oldenburg**, Sitowise Oy (Finland)

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).

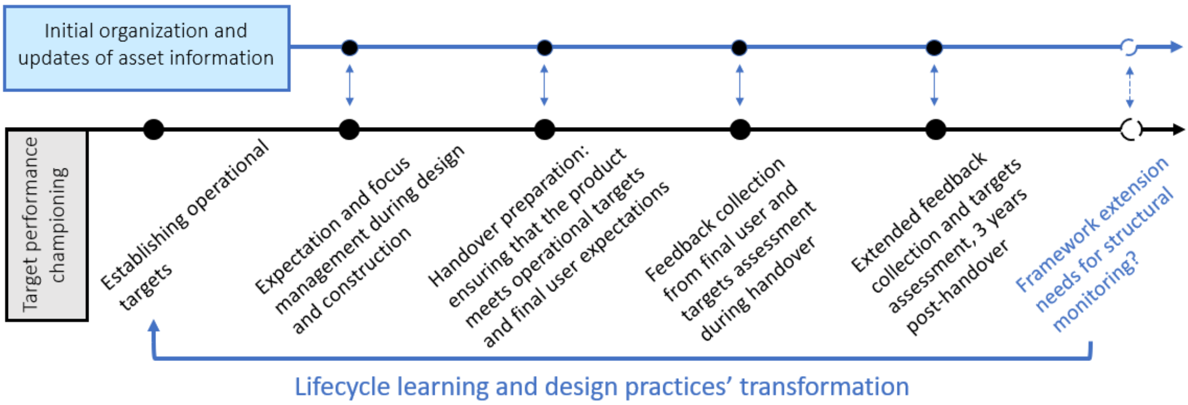

Figure 1: Soft Landings and ISO 19650, basic outline (authors’ summary)

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.

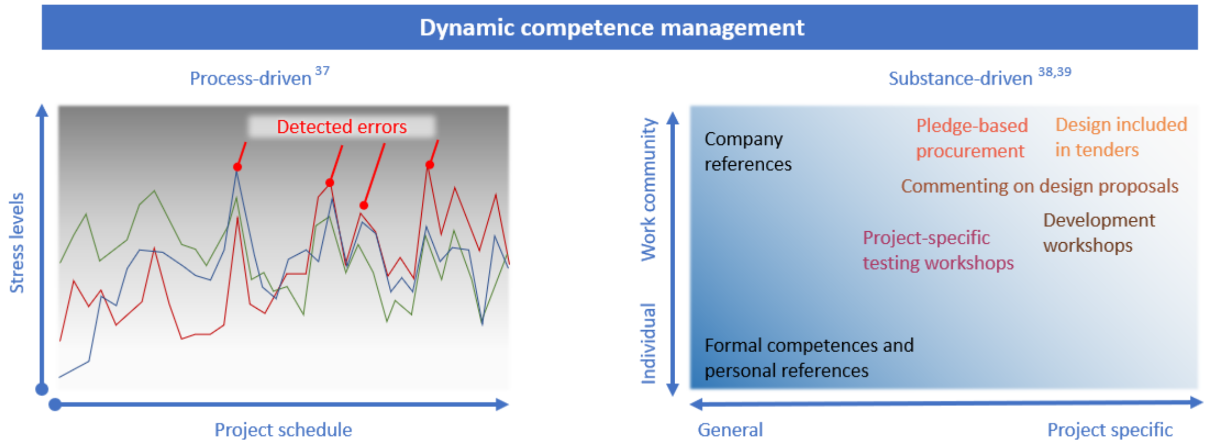

Figure 2: Dynamic competence management methods, basic outline

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.

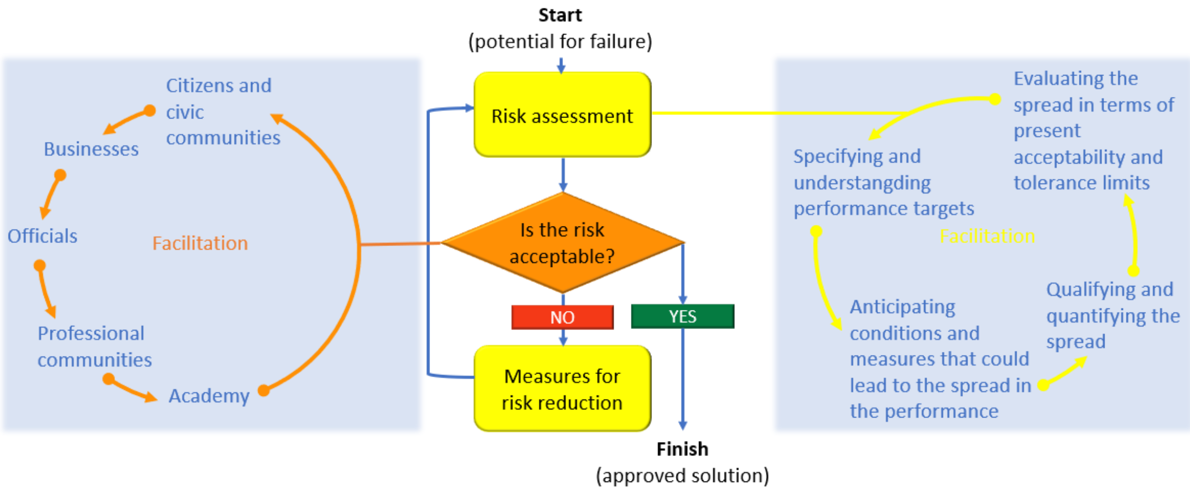

Figure 3: Dialogic and probabilistic methods of risk management (Hagentoft et al., 2015; Larjosto et al., 2021), basic outline (authors' summary)

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

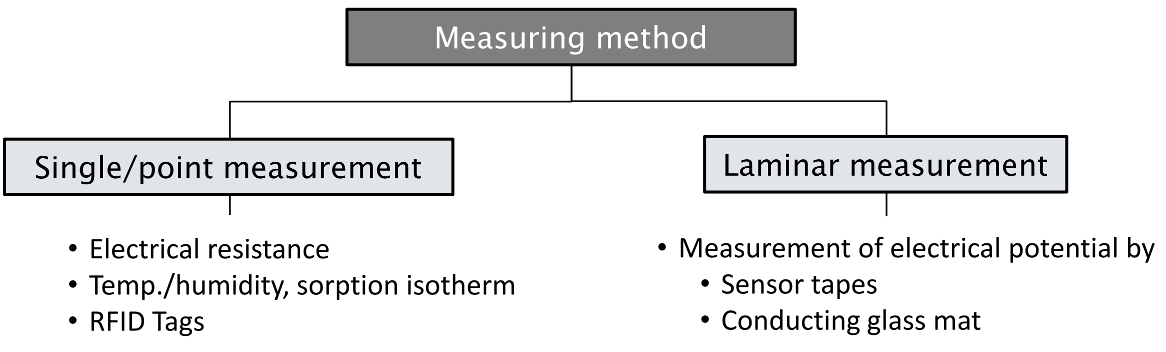

Figure 1: Overview of selected measurement methods for wood moisture content in the monitoring application, Franke et al. (2022)

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.

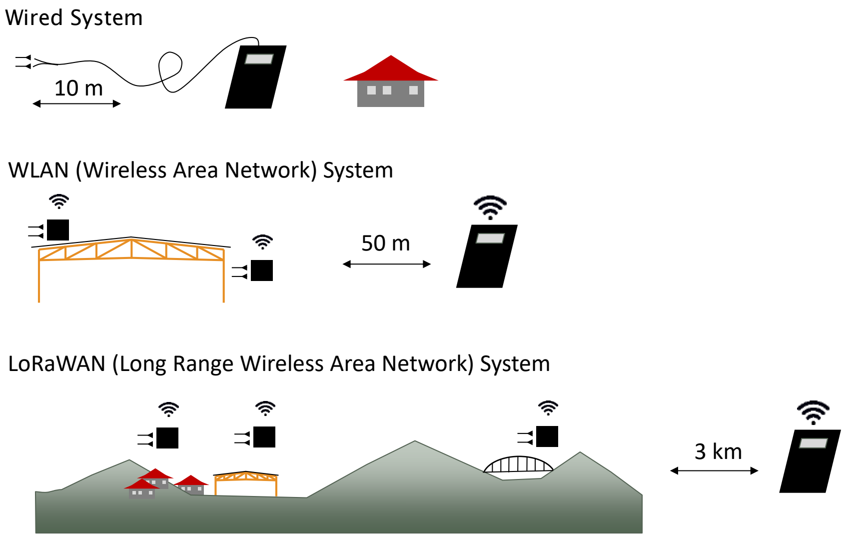

Figure 2: Overview of monitoring system's data management, Franke et al. (2022)

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).

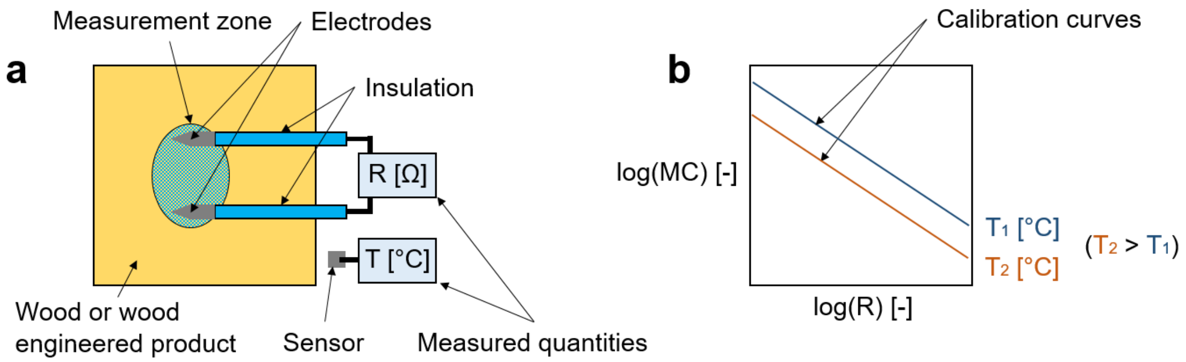

*Figure 1 Electrical resistance method (ERM): a: Setup of measurement (measured quantities: Resistance R, and Temperature T (at surface or close to electrodes)). b: Conversion to wood moisture content (MC) using steady-state-obtained calibration curves for different values of T, shown as linear functions 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.

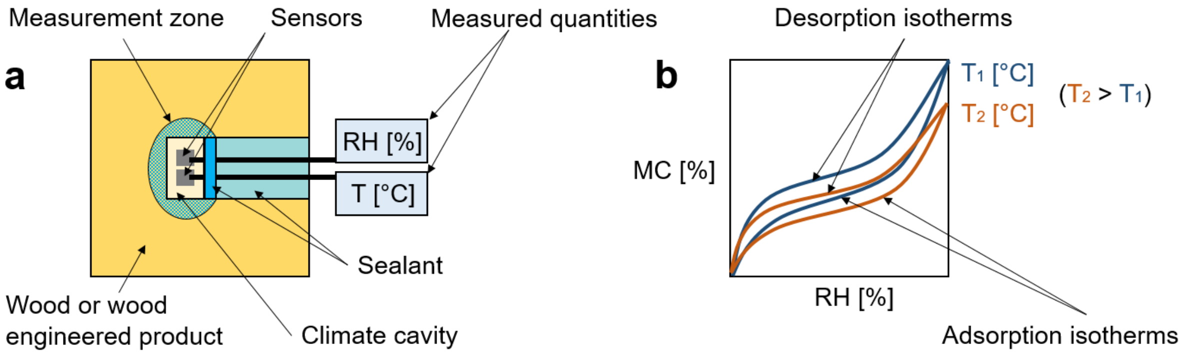

Figure 2 Sorption method (SM). a: Setup of measurement (measured quantities: Relative humidity RH, and Temperature T). b: Conversion to wood moisture content (MC) using steady-state-obtained adsorption and desorption isotherm curves for different values of T.

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

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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.

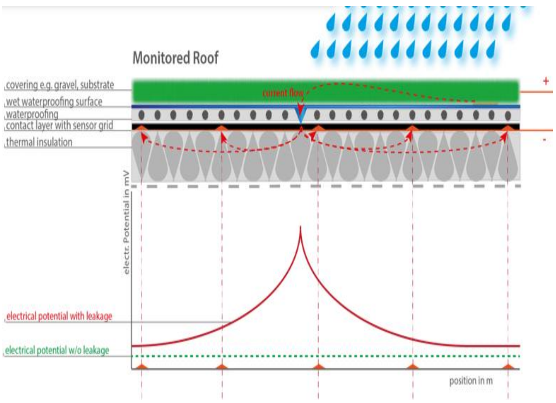

Figure 1 - smartex® mx functional principle

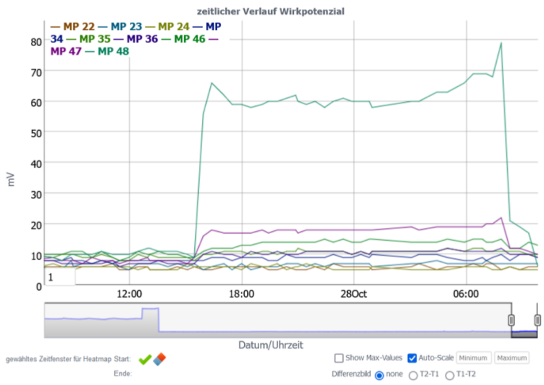

Figure 2 - timeline of measured data w/wo leak

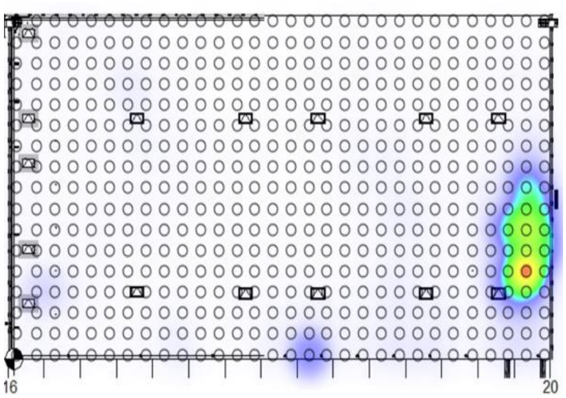

Figure 3 - spatial distribution of measured data with leak

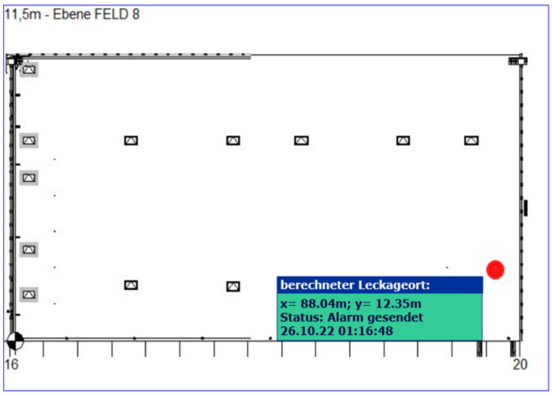

Figure 4 - calculated leak position, roof size appr. 6.000 m²

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.

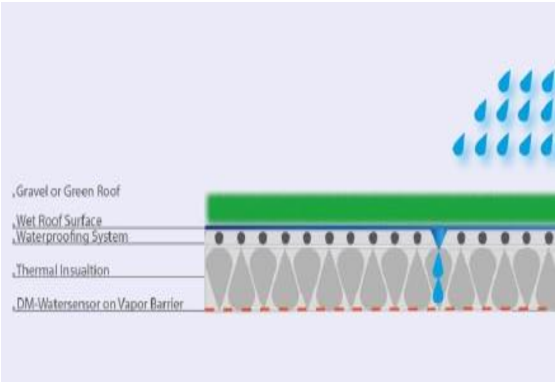

Figure 5 - functional principle smartex® dm

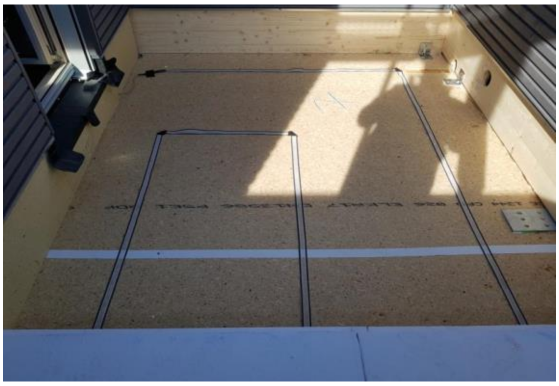

Figure 6 - wooden balcony structure with leak sensor tape

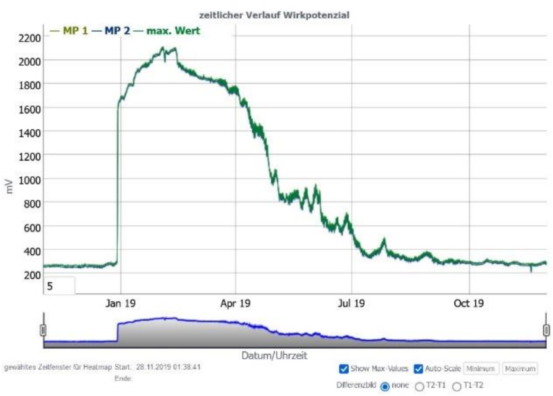

Figure 7 - timeline with water ingress and drying of structure

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

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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 time of wetness, 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 exposure, water penetration, and moisture-driven damage mechanisms 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.

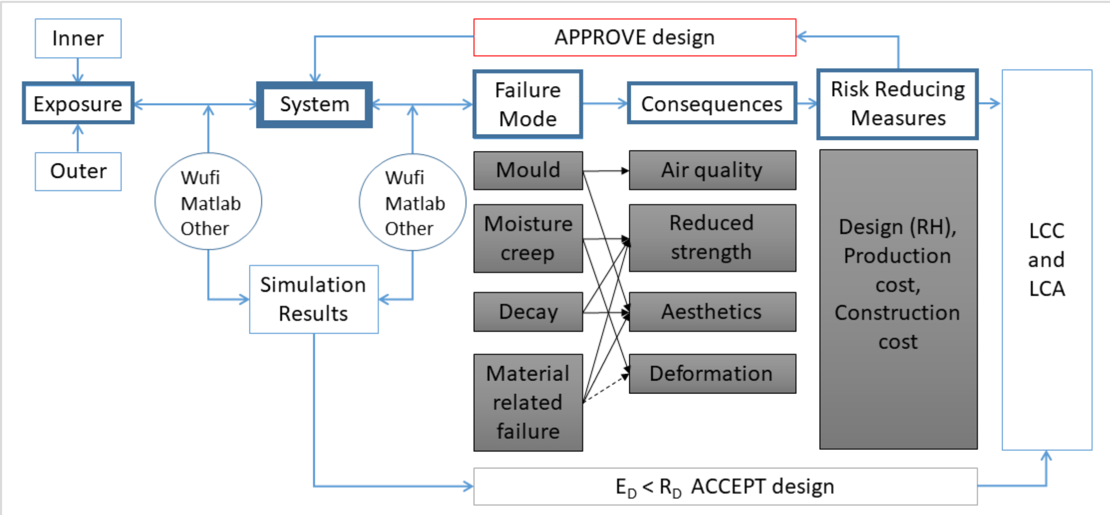

Figure 2: Risk assessment components to calculate the probability of failure. Consequences are matched with costs of repair. Further adjustment with risk reducing measures will show if additional measures are worthwhile.

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

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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).

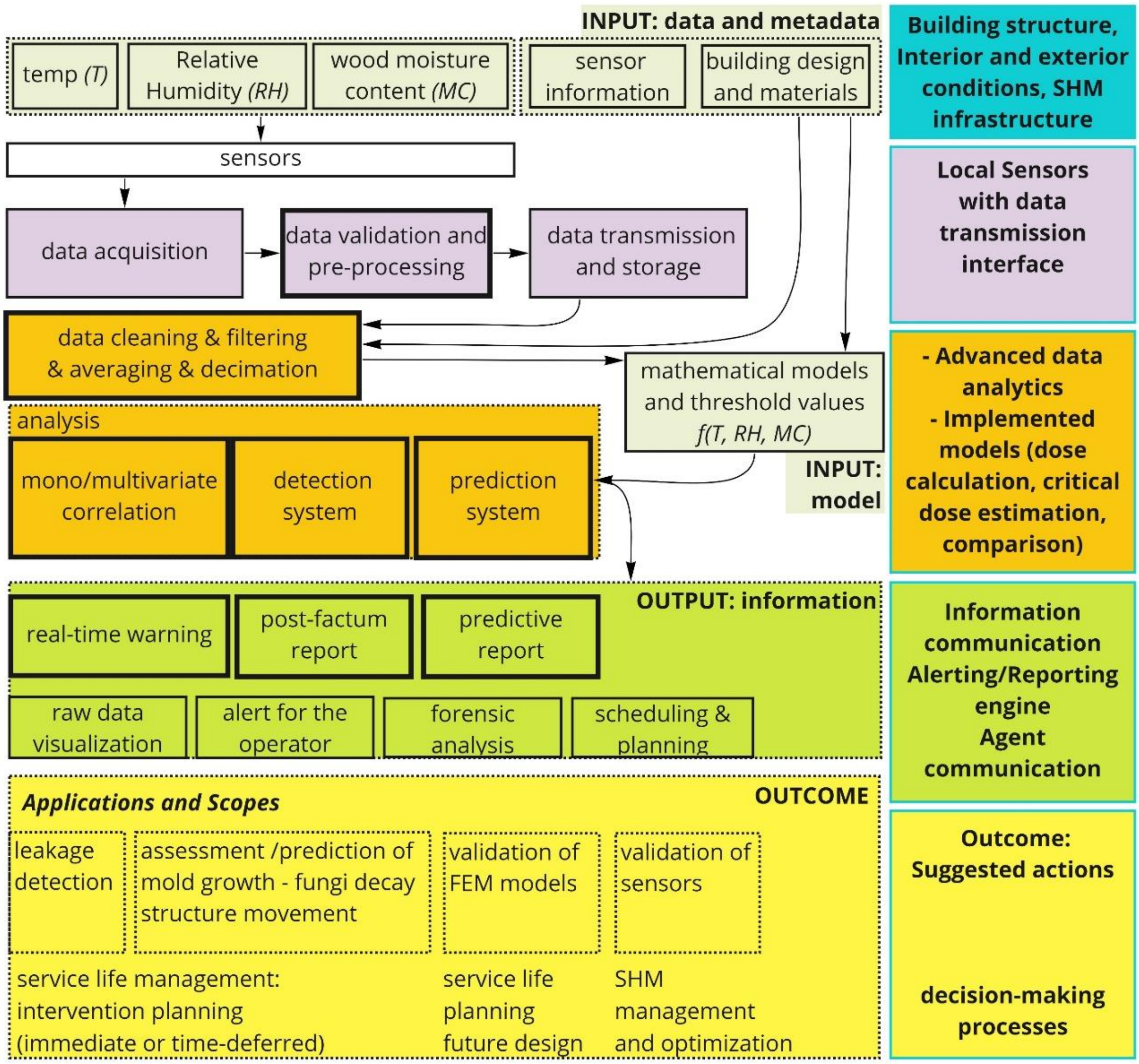

Figure 1 – Hygrothermal monitoring workflow (from Riggio et al. 2022)

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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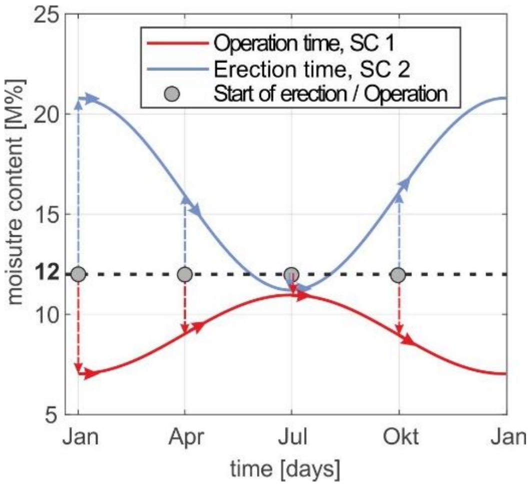
1 Introduction

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:

$$\Delta u_{Surface} = \Delta u_{15\,\mathrm{mm}} \cdot r_u \quad (3)$$

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%

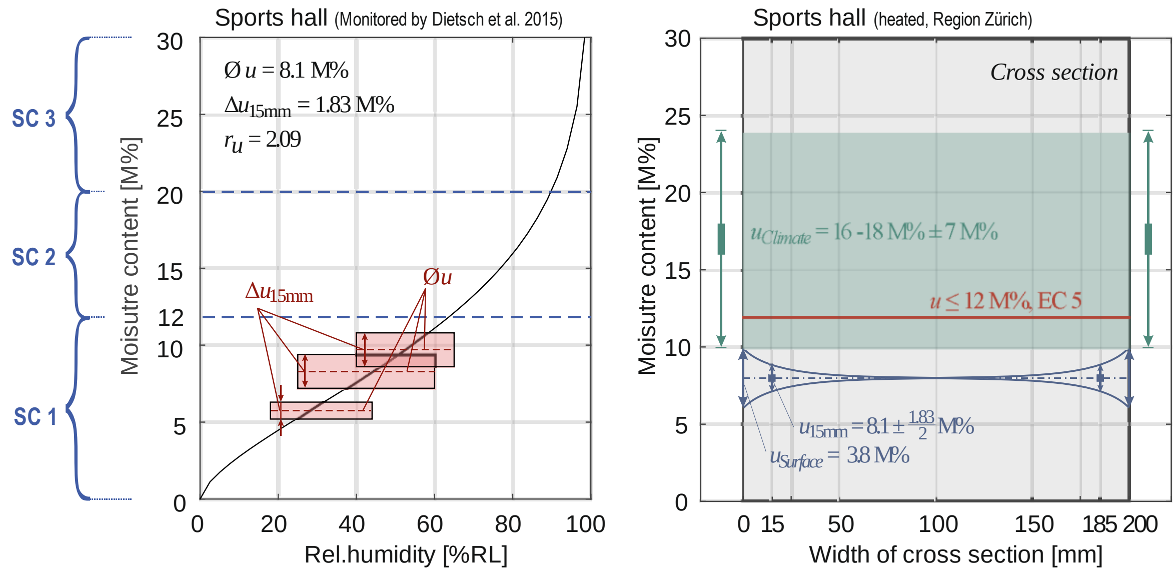


Figure 2 Envelope of sports halls (left) and visualization of expected moisture content over the cross sections (right)

- 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

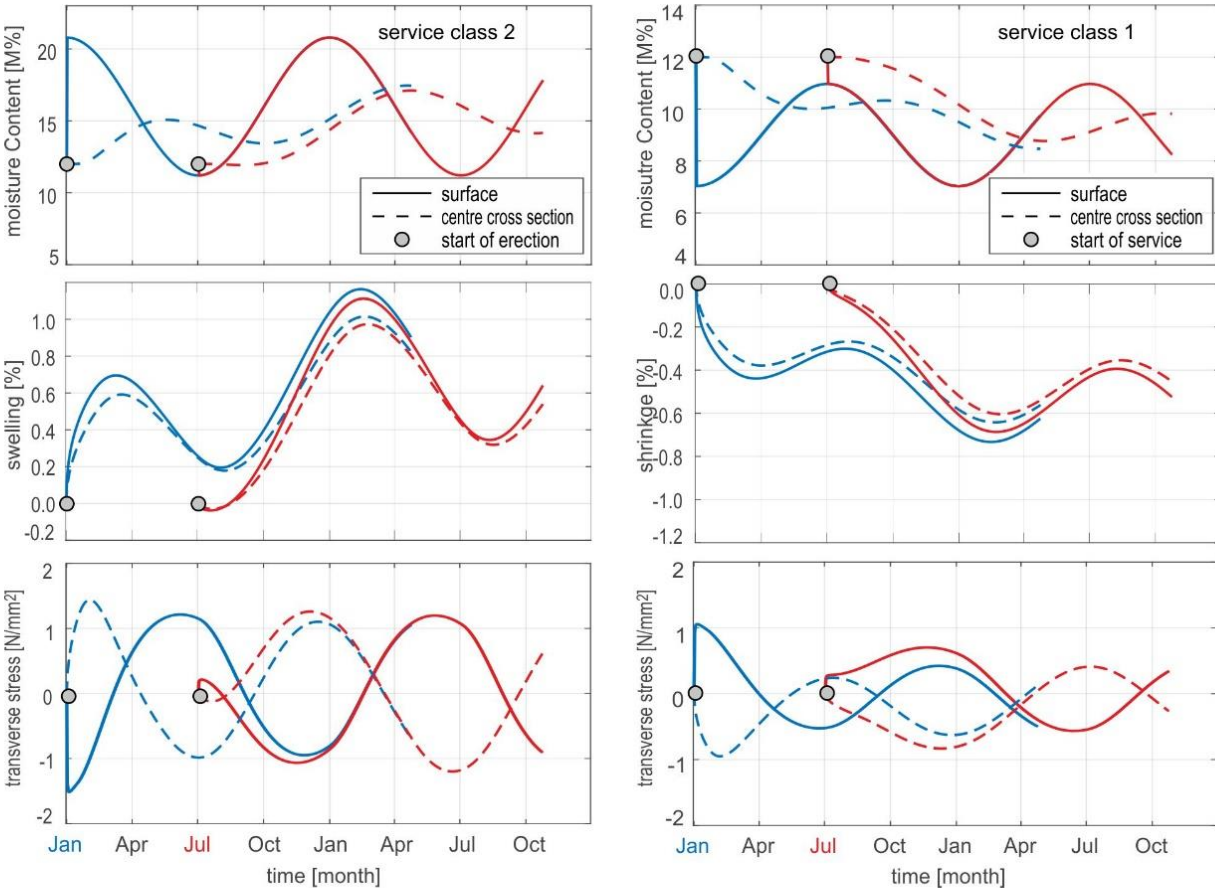


Figure 3 Results of the moisture content (left) and transverse stresses (right) for a cross section of 200/800 mm in Service Class 1 and 2 including seasonal changes of the ambient climate, developed by Franke et al. (2019)

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.

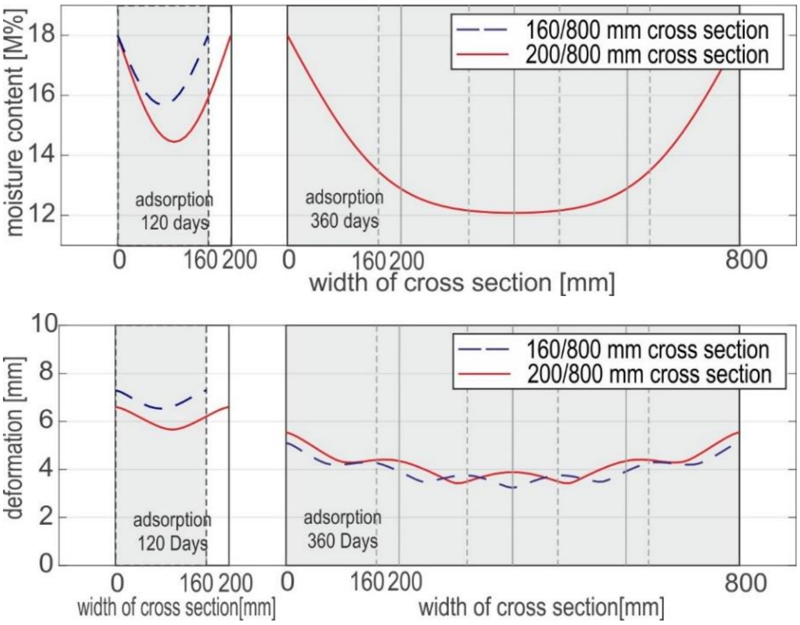

Figure 1 Distribution of the moisture content (left) and deformation (right) of timber beams of different widths subjected to step loads of 6 M% moisture content

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.

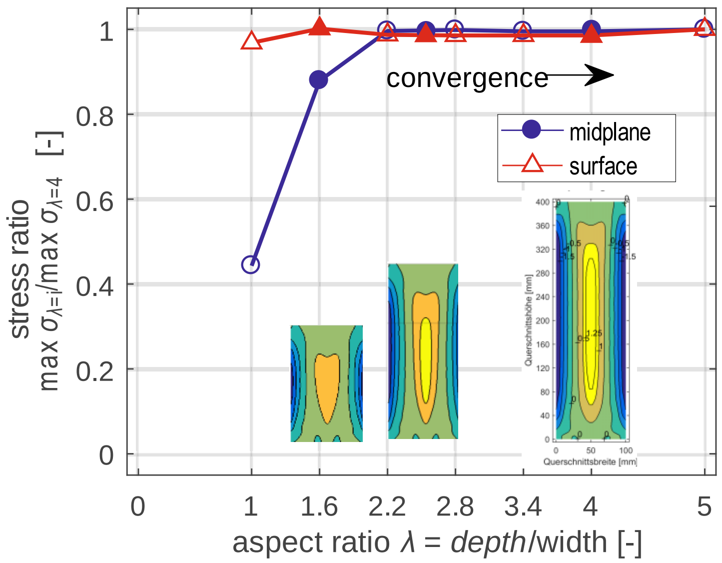

Figure 2 Effect of aspect ratio on stress levels on the surface and midplane of a glulam cross-section

- 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.

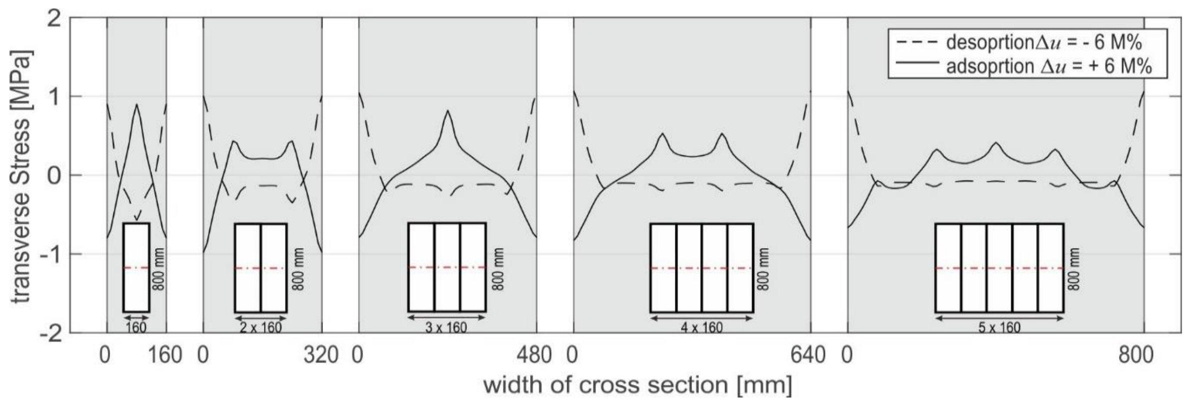

Figure 3 - Transverse stress depending on the width of the cross-section, step load of u = 12 ± 6 M%

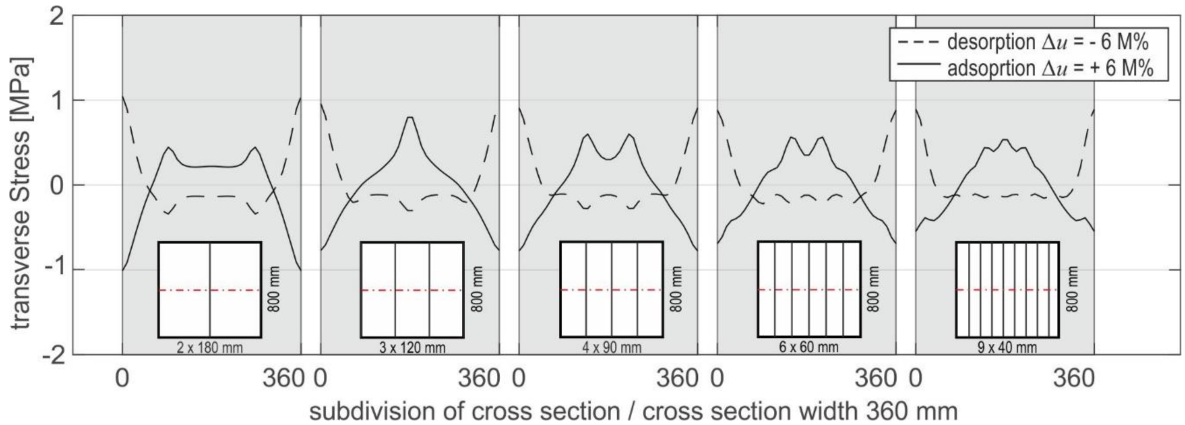

Figure 4 Transverse stresses with different number of beams used in the same cross section width, step load of u = 12 ± 6 M%

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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