FORUM WOOD BUILDING BALTIC 2024

PROCEEDINGS

5th International Conference
Forum Wood Building Baltic
26-28 February 2024
Tallinn, Estonia

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EKA TALTECH FORUM HOLZBAU

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PROCEEDINGS OF THE 5TH FORUM WOOD BUILDING BALTIC 2024

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FORUM WOOD BUILDING BALTIC

Forum Wood Building Baltic is the main conference for architecture and engineering topics of wooden buildings: design for manufacturing and assembly, building physics, energy performance, fire safety etc. in the countries around Baltic Sea. The conference is a part of the international organization Forum Holzbau.

The overarching theme of Forum Wood Building Baltic 2024 is integrated design where different disciplines come together with their own possibilities and limitations to cooperate and push the boundaries of innovation in timber construction.

FORUM HOLZBAU was established 25 years ago as platform of leading universities for knowledge and technology transfer in timber construction and achieves the goal through its pan-European program of conferences and exhibitions.

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CONTENTS

KEYNOTE SESSION 11

Role of New European Bauhaus in the transformation of timber architecture for a sustainable future **12**
Anna Sandak, Eva Prelovšek Niemela, Andreja Kutnar
InnoRenew CoE (Slovenia); University of Primorska (Slovenia)

Designing material genealogies: the case of wood **14**
Aris Kafantaris
Kengo Kuma & Associates (Japan)

Open-Source, Low-Code, No-Code: Digitalization of Renovation Processes **16**
Ergo Pikas, Lauri Koskela, Targo Kalamees, Elisa Iliste, Joosep Viik
Tallinn University of Technology (Estonia)

EUROCODE 5 - 2ND GENERATION 19

Design of Cross-Laminated Timber **20**
Philipp Dietsch, Gerhard Schickhofer, Alfons Brunauer†, Roberto Tomasi, Kay Ackermann, Ulrich Hübner, Harald Krenn, Peter Mestek, Thomas Moosbrugger, Tobias Wiegand
Karlsruhe Institute of Technology (Germany); TU Graz (Austria); Wiehag Timber Construction GmbH (Austria); Norwegian University of Life Sciences (Norway); Fachverband der Holzindustrie (Austria); KLH Massivholz GmbH (Austria) Sailer Stephan Tragwerkteam (Germany); Rubner Holding AG (Austria); Studiengemeinschaft Holzleimbau (Germany)

Design for serviceability limit state – case floor vibration **34**
Tomi Toratti
Federation of the Finnish Woodworking Industries (Finland)

Design of connections **44**
Robert Jockwer
Chalmers University of Technology (Sweden)

Design of timber bridges **54**
Matthias Gerold
Harrer Ingenieure GmbH (Germany)

Fire Design **64**
Alar Just, Andrea Frangi, Jouni Hakkarainen, Joachim Schmid, Norman Werther, Harald Krenn, Renaud Blondeau
Tallinn University of Technology (Estonia); ETH Zürich (Switzerland); Eurofins Expert Services (Finland); Technical University of Munich (Germany); KLH (Austria); Stora Enso (France)

DESIGN FOR MANUFACTURE AND ASSEMBLY 75

The future of timber construction facing the challenges of Industry 4.0 **76**
Dr. h.c. Heinz Köster
Technical University Rosenheim (Germany); Forum Wood Building

Concept building designs for DfMA with timber **80**
Sebastian Alejandro Hernandez Maetschl
Stora Enso (Germany); Ramboll Finland (Finland)

ELEMENTerial – Construction system study for CLT offcuts 92
Siim Tuksam, Sille Pihlak
Timber Architecture Researh Center PAKK, Estonian Academy of Arts (Estonia)

TIMBER BASED RENOVATION SOLUTIONS 95

Circular renovation of an apartment building with prefabricated insulation elements 96
Eero Nigumann, Targo Kalamees, Kalle Kuusk, Peep Pihelo
Timbeco Ehitus OÜ (Estonia); nZEB Research Group, Tallinn University of Technology (Estonia)

Development of prefabricated additional insulation elements for the renovation of high-rise apartment buildings 98
Peep Pihelo, Targo Kalamees
nZEB Research Group, Tallinn University of Technology (Estonia)

Case studies of moisture safety implementations on timber structures 100
Eneli Liisma, Rauno Lemberg, Erik Sumeri, Daniil Khaustov, Aleksandr Gildi
AS Merko Ehitus Eesti (Estonia)

Commissioning the Design and Construction of Prefab Renovation 102
Alari Jürgenson, Peep Pihelo
Tallinn University of Technology (Estonia)

Misused timber in renovation 110
Üllar Alev
Tallinn University of Technology (Estonia)

REGENERATIVE AND CIRCULAR ARCHITECTURE 119

3cycle. An open source circular modular construction system 120
Renee Puusepp
Timber Architecture Research Center PAKK, Estonian Academy of Arts (Estonia)

Prolonged carbon storage and CO2 reduction by circular design with wood 122
Harald Schwarzschachner, Sebastián Hernández-Maetschl
Stora Enso (Austria); Stora Enso (Germany)

Prefab light clay-timber elements for net zero whole-life carbon buildings 124
Juha Päätalo, Jaan Kers, Anti Rohumaa, Johanna Liblik, Kimmo Lylykangas
Päätalo Architects Ltd (Finland); Tallinn University of Technology (Estonia)

Fabrication reconsidered: Root chair; robotic milling technology 126
Hugo Fekar, Jan Novák, Viktória Žigmundová, Jakub Míča, Diana Suleimanova
Academy of Arts, Architecture and Design in Prague (Czech Republic)

LIFE-CYCLE-COSTING IN WOOD CONSTRUCTION 137

Modelling the decay risk of exterior wood from detailed 3D geometries 138
Jonas Niklewski, Richard Acquah, Philip Bester van Niekerk, eyyed Hasan Hosseini, Anna Sandak, Jakub Sandak
Lund University (Sweden); InnoRenew CoE (Slovenia); University of Primorska (Slovenia); University of Göttingen (Germany)

Bioinspired living coating system for regenerative and circular architecture 140
Anna Sandak, Karen Butina Ogorelec, Ana Gubenšek, Faksawat Poohphajai
InnoRenew CoE (Slovenia); University of Primorska (Slovenia); Aalto University (Finland)

Tool development for LCC of wooden building envelope 142
Roja Modaresi, Magnus Landaas
Norwegian Institute of Wood Technology (Norway)

The Effect of Material Selection, Design, and Construction on the Service Life and Appearance of a Wooden Building 144
Villu Kukk, Jürgen Hiiekivi, Targo Kalamees
nZEB Research Group, Tallinn University of Technology (Estonia)

MOISTURE SAFETY 147

Determining Moisture Content of Laminated Veneer Lumber (LVL) 148
Inger Merete Birkeland, Erlend Andenæs, Lars Gullbrekken, Tore Kvande

The future of wooden structures in combination with bio-based insulation 150
Anke Blommaert, Nathan Van Den Bossche, Marijke Steeman
Ghent University (Belgium)

A numerical study of methods to improve moisture safety of ventilated wooden roofs 152
Klaus Viljanen, Laurina Felius
Aalto University (Finland); Ramboll Finland Oy (Finland); Rambøll Norge AS (Norway)

Moisture safety strategies for roof renovation with prefabricated additional insulation elements 154
Georg-Mihkel Kodi, Kristo Kalbe, Peep Pihelo, Targo Kalamees
Tallinn University of Technology (Estonia)

A novel approach to quantify crack formation in CLT 156
Kristo Kalbe, Targo Kalamees
Tallinn University of Technology (Estonia)

TIMBER STRUCTURES 159

Reconnect Ukraine – research project on timber connections 160
Andrii Bidakov, Robert Jockwer, Alar Just, Eero Tuhkanen, Dmitrii Kochkarev
O.M.Beketov National University of Urban Economy in Kharkiv (Ukraine); Chalmers University of Technology (Sweden); Tallinn University of Technology (Estonia); National University of Water and Environmental Engineering (Ukraine)

Assessment of strength and stiffness properties of aged structural timber 170
Maarja Kauniste, Alar Just, Eero Tuhkanen
Tallinn University of Technology (Estonia); RISE Research Institutes of Sweden (Sweden); Arro & Agasild Inseneribüroo OÜ (Estonia)

Bending and vibration behaviour of CLT-steel composite beams 172
Noah Böhm, Bertram Kühn, Achim Vogelsberg
Technische Hochschule Mittelhessen – University of Applied Sciences, Gießen (Germany)

On-site application of end-grain bonded timber under low curing temperatures 174
Dio Lins, Steffen Franke
Bern University of Applied Sciences (Switzerland)

PROCESS INNOVATION 177

Planning sustainability for timber construction projects - example of the Student residential quarter "Campus RO" 178
Lore Köster
Planungsbüro Köster, Stephanskirchen (Germany)

Multi-criteria decision support tool for selection of biobased facade materials 180
Veronika Kotradyová, Anna Sandak, Jakub Sandak, Gry Alfredsen
BCDlab, Faculty of Architecture and Design, STU in Bratislava (Slovakia); InnoRenew (Slovenia); University of Primorska (Slovenia); Norwegian Institute of Bioeconomy Research (Norway)

Revitalizing Modernist Districts: Neighbourhood Level Mass-Renovation with SOFTacademy project 182
Murel Truu, Lauri Lihtmaa, Mariliis Niinemägi
Tallinn University of Technology (Estonia); Tallinn City, Strategic Management Office (Estonia)

Airtightness and moisture behaviour of joints and VOC concentrations in wood and hybrid structures 184
Anti Rohumaa, Simo Erkko, Pertti Pasanen, Marko Hyttinen
South-Eastern Finland University of Applied Sciences (Finland); University of Eastern Finland (Finland)

Timber Reciprocal Frame Structures 192
Kertu Johanna Jõeste
Estonian Academy of Arts (Estonia)

HISTORIC WOODEN BUILDINGS 203

Technical state, renovation need, and performance of renovation solutions of Estonian wooden log houses 204
Alois-Andreas Põdra, Gert Air Allas, Aime Ruus, Elo Lutsepp, Targo Kalamees
Estonian Open Air Museum (Estonia); Tallinn University of Technology (Estonia)

Low carbon emission renovation of historic residential buildings 206
Kadri-Ann Kertsmik, Endrik Arumägi, Jaanus Hallik, Targo, Kalamees
Tallinn University of Technology (Estonia)

Assessment of the Potential of Reconstruction of Historic Buildings 208
Elina Liiva, Helena Rummo, Kateriin Ambrozevits, Andres Ojari, Targo Kalamees, Siim Lomp
Estonian Academy of Arts (Estonia); Tallinn University of Technology (Estonia)

SPONSORS AND EXHIBITORS 211

KEYNOTE SESSION

Role of New European Bauhaus in the transformation of timber architecture for a sustainable future
Anna Sandak, Eva Prelovšek Niemela, Andreja Kutnar

Designing material genealogies: the case of wood
Aris Kafantaris

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Role of New European Bauhaus in the transformation of timber architecture for a sustainable future

Anna Sandak [1,2], Eva Prelovšek Niemela [1], Andreja Kutnar [1,2]

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[2] University of Primorska, Slovenia

Summary

Europe has the ambition to become the world's first climate-neutral continent. The European Union has implemented a range of policies to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels. With around 40% of GHG emissions from building operations and an additional 10-20% from embodied emissions, the construction ecosystem is one of the major contributors to the climate crisis, making it an ideal sector for transformation.

The New European Bauhaus (NEB) is a creative initiative that connects the European Green Deal to our daily lives and living spaces. NEB is an inspired movement to facilitate and steer the transformation of our societies along three inseparable values: sustainability (from climate goals to circularity, zero pollution, biodiversity), aesthetics (quality of experience and style beyond functionality), and inclusion (from valuing diversity to securing accessibility and affordability).

At InnoRenew CoE we were aware of the necessity for change when we started designing our building in 2017. With an ambition to contribute towards the transformation of the built environment, we constructed the biggest wooden building in Slovenia in 2021, which was recognized as a best practice of the New European Bauhaus. Our building is a research object on its own. It provides new and pertinent information about the performance of timber buildings in general, and specifically in Slovenia's sub-Mediterranean coastal climate where events like earthquakes and strong winds must be considered. The exemplary characteristics of the three core values of NEB and the three working principles of the NEB implemented by our building can be summarized:

- Sustainability: Use of timber as the main building material; restorative, environmental, and ergonomic design (REED); data and new knowledge on the performance of timber buildings; 3,000 trees planted to offset the carbon footprint of the construction.
- Aesthetics and quality of experience: Use of natural light, air quality control, acoustic elements, open spaces for social interaction and physical movement, views to the outdoors and of the building interior, outdoor areas with particular microclimatic zones, green roofs, terraces where employees can relax; in addition, it provides a habitat for numerous insects and birds.
- Inclusion: Designing the largest timber building in Slovenia was a complex task that went beyond just designing a functional building. It has been clearly demonstrated that the physical transformation of a place defined as post-industrial can bring in a new spirit and sociotechnical development. The project has ambitiously brought new knowledge to the local community and the nation in general. By creating an engaging new science hub that enhances collaboration between research institutes, universities, private companies, vocational trainers, schools, and the local, national, and international community, InnoRenew CoE has become a significant landmark in Slovenia.
- Participatory process: While planning the building we used the process of co-creation with our staff, our project partners, and professionals at the University of Primorska. A broad number of professionals helped to develop the concept of the building that includes diverse laboratories and conference premises. During the planning phase, we

established a collaboration with the Municipality of Izola, which became a Living Lab golden member. Building on this connection, we were able to connect with the local community and collaborate on several projects.

- Multi-level engagement: We collaborated horizontally with national and international partners on the development of the building project and the use of ERDF funding. The major partners are the University of Primorska, the Slovenian National Building and Civil Engineering Institute, the Institute of the Republic of Slovenia for the Protection of Cultural Heritage, and Fraunhofer WKI. Stakeholder representatives from across the globe served as the institute's Council of Experts. The added value of this collaboration was an international and multidisciplinary approach that opened the design of the building and the organization's operations and services to broader perspectives.
- Transdisciplinary approach: At InnoRenew CoE architects, engineering professionals, researchers, material scientists, health researchers, art historians, community members, and woodworkers all come together. For instance, our biologists worked together with the architects in the selection of optimal bio-based coating systems and effective treatments for exterior wood materials.

The innovative character of the building and the InnoRenew CoE project was built around three main attributes. First, this building is InnoRenew CoE's own sustainable and healthy building design paradigm, where REED was used from the beginning of the project. Second, the building is both the result of state-of-the-art and ongoing research and is itself a research object. Third, the building is the largest wooden building in Slovenia and an attraction point for scientists, professionals, students, pupils, and the public regarding the multidisciplinary exchange of knowledge in the field of renewable materials and healthy buildings. InnoRenew CoE has increased the quality and value of renewable material education in the region by establishing a new PhD program "Renewable Material for Healthy Built Environment", at the University of Primorska. We coordinate the working group on Education and Vocational Training in the woodPoP initiative. Additionally, we publish articles about the research we conduct, which aims to increase the acceptance of renewable materials among the wider public and provides an important basis for future research and development activities in the field.

The twin green and digital transformation of the construction ecosystem is an enormous opportunity to create sustainable employment in urban and rural areas. The significant bottleneck for the transformation of the construction ecosystem is the massive need for skilled workers and educated professionals at all levels, since more than three-quarters of companies in the EU report difficulties in finding workers with the required proficiencies. Acceleration of upskilling and reskilling the current and future workforce is necessary to transition to a carbon-neutral, resilient, domestic sustainable construction sector in Europe. To address this issue, the EC President announced the New European Bauhaus Academy (NEBA) as the principal flagship of the NEB. We are proud that InnoRenew CoE is the headquarters of the NEB Academy Pioneer Hub for Sustainable Environments with Renewable Materials.

Key words: New European Bauhaus; aesthetics; sustainability; inclusion; construction sector; timber architecture; NEB academy

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Designing material genealogies: the case of wood

Aris Kafantaris, Designing material genealogies: the case of wood [1]

[1] Kengo Kuma & Associates (KKAA), Japan

Summary

The keynote presentation focuses on a series of seven projects designed by Kengo Kuma & Associates (KKAA) from 2007 to 2014. The projects are presented as intermediate steps within a framework of continuous evolution of a structural system based on wood elements. The structural system starts as a wooden toy called 'chidori' and evolves in terms of scale, geometry, orientation, detailing and material. The framework linking the projects together was initially developed for KKAA's 2016 submission in Venice Architecture Biennale, and the 2019 exhibition 'A Lab for Materials'.

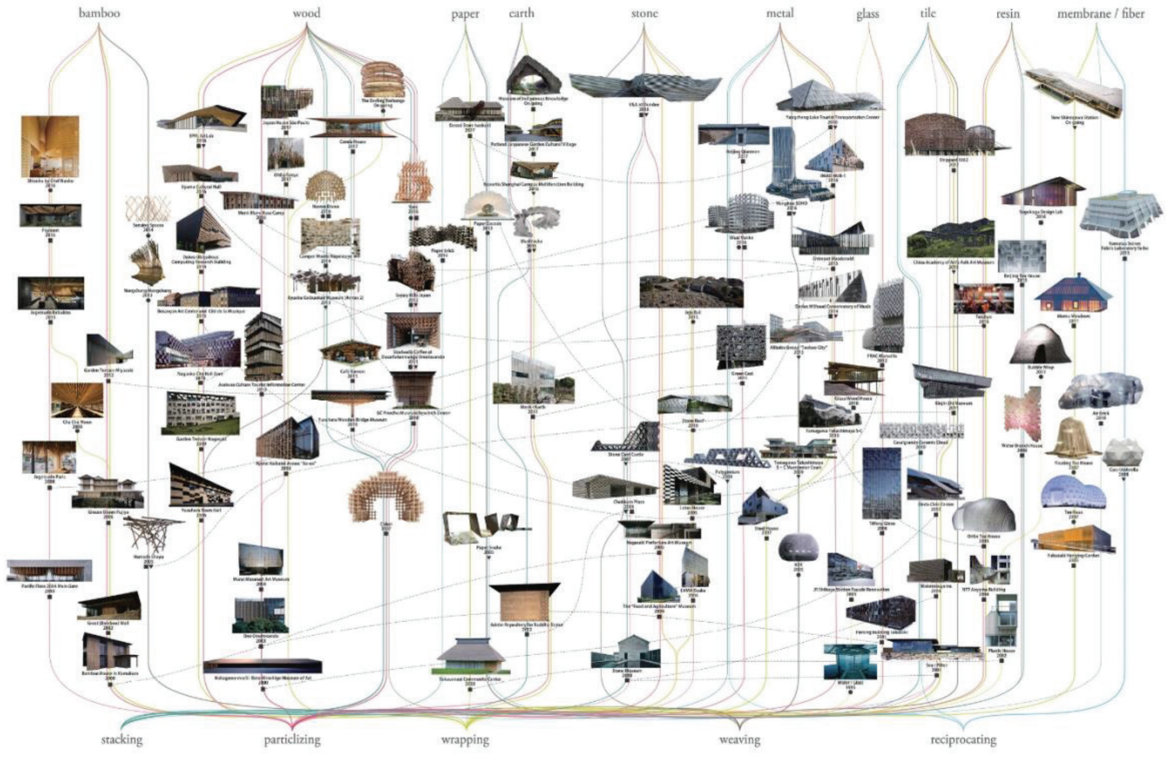

Figure 1 'Lab for Materials' Tree diagram, from the 2019 Exhibition in Tokyo Station Gallery, Tokyo, Japan

1. Conclusions

A lot of KKAA's output has been in wood or wood-related materials such as thatch, bamboo, bark, paper, etc. The office has been designing and building structures using natural or hybrid materials for more than three decades, and in that time, has developed a particular design/research methodology.

The methodology is material-centric, and specifically focused on first defining a unit (or cell, or module) that when aggregated, would create a desired assembly. The units are often sized in such a way that they can be carried, installed, and manipulated by unassisted workers, using their hands and simple tools. The original geometry of the unit, combined with its material properties as well as the rule for aggregating several units, will infer different properties to the macro-assembly. These aggregated macro-assemblies adopt multiple roles: structural frames, façade systems, shading or privacy screens, or furniture. They are multifunctional and multimodal.

One very important implication of designing with a rule-based process, is that the rules can be evaluated after their application, tweaked, iterated on, and re-applied at the next project. This creates entire series or lineages of projects, where one can trace the evolution of a design idea -an original unit with its aggregation rules- as it changes from project to project and adapts to different requirements. We argue that this is a novel way of treating design as a process that does not stop with the realization of a project, but rather continues across several of them – and that the thing being designed is not an object, or a building, but an evolving system.

One particular lineage called “wood-weaving” is a clear showcase of the above process unfolding across seven projects in seven years and has been examined in more detail. It tracks the application of the ‘chidori’ toy joint applied to a small open pavilion, the evolution of the joint system into a structural grid for a gallery, the shrinking and adaptation of it to a furniture system, the rescaling and deformation to make a non-structural façade screen, the reorientation of the façade system and its transformation to a structural system, the radical simplification of said system for a small pavilion, and finally, the application of this simplified system to a pavilion made of stone mimicking the proportions and joinery of wood, reinforced with wooden joints.

The journey through these projects takes place through the help of the tree diagram that was first put together for the 2019 Exhibition ‘Lab for Materials’ which was an evolution of an idea first applied in the 2016 Venice Biennale with the KKAA pavilion called “Small Architecture Research Genealogies”. The tree diagram is recognized as a non-strict taxonomy, that is nevertheless employed as a conceptual map for future research.

Figure 2 The ‘chidori’ lineage, from traditional joint to a series of derived systems

2. Acknowledgements

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Open-Source, Low-Code, No-Code: Digitalization of Renovation Processes

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Summary

The slow yet accelerating adoption of digital technologies in the European construction industry emphasizes the strategic importance of digitalization and automation for sustainability and resilience. However, 95% of companies in the construction sector, especially those involved in renovating buildings, are small- and medium-sized enterprises. SMEs are significant in Europe's ambition for climate neutrality by 2050. It is proposed that open-source, low-code, and no-code technologies facilitate SMEs' digital transformation, enhancing innovation and supporting sustainable practices.

Key words: Digitalization of renovation processes, SMEs, digital transformation, low-/no-code, open-source

1. Introduction

The construction industry has slowly implemented digital technologies in planning, designing, and managing construction processes, products, and services. However, the situation is rapidly changing. Digitalization and automation are considered in the European Commission’s new industrial strategy and the High-Level Construction Forum's transition pathway as key strategic measures for the sustainable and resilient transformation of the European built environment and the construction industry.

However, the challenge is that most European construction sector companies are small and medium enterprises (SMEs). These SMEs face challenges, especially in the financial and economic turmoil, in digitalizing processes, products, and services. This is especially true for companies renovating residential buildings (Pikas et al., 2021). Small companies lack skilled labor and resources to invest in digital solutions, methods, tools, and training to implement these technologies. This is where open-source (Bolpagni et al., 2022), low-code, and no-code (Martinez and Pfister, 2023) solutions can be handy. The upfront investments in digital transformation do not need to be resource-intensive.

2. Background

Europe aims to become a climate-neutral economy by 2050 (European Commission, 2020a), and the built environment and construction play an important role in the vision (European Commission, 2023a). Many initiatives for the built environment and construction industry have been introduced, including a **renovation wave** (European Commission, 2020b), the **New European Bauhaus** (European Commission, 2023b), and proposals to amend significant construction sector regulations, such as the **European Construction Products Regulation** (European Commission, 2022) and the **Energy Performance of Buildings Directive** (Parliament and Council, 2021).

Revising key construction regulations aims to decrease greenhouse gas emissions, enhance energy efficiency, promote renovation, decarbonize building processes and the built environment, use renewable energy, and improve building performance data management (Parliament and Council, 2021). The directives also encourage measures that promote the reduction of new and reuse of existing building materials, enabled by circular construction. These require changes and adaptation from both the demand and supply sides and all levels of European society.

From the supply perspective, the new industrial strategy for the construction sector emphasizes a rapid digital transition and collaboration between different stakeholders (European Commission, 2020c). The sector needs to transform its **business models**, **value**, and **supply chains**, requiring developing and implementing feasible transition plans. The **High-Level Construction Forum** proposed the transition pathway blueprint with preconditions and necessary actions to achieve the green, digital and resilient targets of the built environment and construction sector (European Commission, 2023c).

Central in this is the utilization of **novel digital technologies**, increasing innovative entrepreneurship through the share of **start-ups**, and improving the resilience of construction **value and supply chains**. The European Digital Decade is the vision of the digital transformation of the Europe by 2030, including also construction as an economic sector. The four key areas of digital transformation include (1) digital skills, (2) secure and sustainable digital infrastructure, (3) digital transformation of businesses, and (4) digitalization of public services. Cultivating digital skills and transforming SMEs is the key to digitalization in the construction.

3. Results and discussion

95% of construction sector companies create ca 18 million direct jobs and about 9% of the EU's GDP. That is, construction sector is highly fragmented and described by lack of capabilities and resources to invest in the digital transformation. Based on the initial literature review, the role of the open source and low-code/no-code technologies could include:

1. **Facilitate Digital Adoption**: Low-code/no-code platforms can significantly lower the barrier to digital transformation for SMEs in the construction sector.
2. **Enhance Innovation and Collaboration**: Open source technologies can foster innovation and collaboration among construction SMEs. By using and contributing to open source tools, companies can benefit from the collective intelligence.
3. **Improve Skills and Talent Development**: Implementing low-code/no-code and open source technologies requires a shift in skills development within the construction industry. Upskilling and reskilling the existing workforce to navigate and contribute to these platforms can enhance employee satisfaction, extend careers, and attract new talent.
4. **Support Sustainable and Circular Construction**: Digital tools developed through low-code/no-code platforms and open source technologies can support sustainable and circular construction practices .
5. **Overcome Challenges**: By embracing low-code/no-code and open source technologies, SMEs can overcome many hurdles of digital transformation.

4. Conclusions

For the European construction industry to meet the ambitious renovation and decarbonization targets, SMEs must adopt digital technologies. Low-/no-code and open source technologies offer practical, accessible paths for SMEs to the digital transformation. These technologies do not only enable achieving EU's climate neutrality and digitalization goals but also enhance the competitiveness and resilience of the construction industry.

5. Acknowledgements

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FORUM
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EUROCODE 5
2ND GENERATION

Design of Cross-Laminated Timber
Philipp Dietsch, Gerhard Schickhofer, Alfons Brunauer†, Roberto Tomasi, Kay Ackermann, Ulrich Hübner, Harald Krenn, Peter Mestek, Thomas Moosbrugger, Tobias Wiegand

Design for serviceability limit state – case floor vibration
Tomi Toratti

Design of connections
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Design of timber bridges
Matthias Gerold

Fire Design
Alar Just, Andrea Frangi, Jouni Hakkarainen, Joachim Schmid, Norman Werther, Harald Krenn, Renaud Blondeau

Eurocode 5 – 2nd Generation – Design of Cross-Laminated Timber

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Summary

The development of cross-laminated timber (CLT) over the past 20 years represents a significant progress for the timber construction sector illustrated e.g. by the tall timber movement. Consequently, it is evident to introduce this now commonly established timber product into European design standards. This contribution features the key contents and background information on the new developed sections for the design of *cross-laminated-timber* for the next generation of Eurocode 5. It also elucidates changes compared to previously applied design methods.

Key words: Eurocode 5; Cross-laminated timber; Reinforcement; Self-tapping screws; Wall diaphragms; Concentrated loads; Shear failure mechanisms;

1. Introduction

Since the first pilot projects and technical approvals in the mid-1990s, cross-laminated timber (CLT) has undergone impressive development [1]. The continuously growing number of production facilities and general technical approvals (abZ) or European Technical Assessments (ETA) clearly demonstrate the increasing acceptance and attractiveness of this now-established construction product. The industrial production of CLT enables a high degree of prefabrication; large-format wall, ceiling, and roof elements, including openings and conduit routing, can easily be manufactured. On the construction site, these elements can be assembled quickly and easily, for example, using fully-threaded screws [2]. CLT elements are predominantly used in the construction of single and multi-family homes, multi-story residential buildings, schools, and commercial structures.

The current version of the European design standard for timber structures, Eurocode 5, [3] does not include specific provisions for the design of cross-laminated timber. The code-compliant application of cross-laminated timber has only been made possible in a few European countries through non-contradictory complementary information to Eurocode 5 (NCCI) in the national annexes (NA) [4], [5]. To address the evident gap in Eurocode 5, the design of *Cross-Laminated Timber* has been prioritized on the list of work items for its revision [6].

2. Method

As illustrated in Figure 1, standardization is the consequence of successful research and development, which has found positive application and acceptance in practice. According to the European position on standardization, harmonized technical rules for common design cases should be developed, containing only rules based on widely accepted research results that have been validated through sufficient practical application and related experiences. The target group for such design rules is structural engineers with at least 3 years of experience in the respective field — qualified professionals capable of working independently in their field [7].

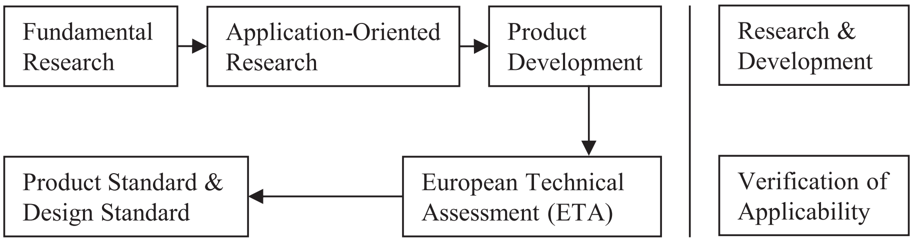

Figure 1 Development of products and the path to their applicability in practice

The development of design approaches for construction products requires standardized testing procedures and a product standard or a European Technical Assessment (ETA) to be applicable. The work on European design standards is structured as illustrated in Figure 2 and [8]. The European standardization committee CEN/TC 250 has a mandate to further develop design rules for the construction industry. This committee is divided into 11 sub-committees; CEN/TC 250/SC 5, one of these sub-committees, is responsible for all parts of Eurocode 5 (EN 1995). National standardization bodies (e.g., DIN) send delegates to these sub-committees through their mirror committees. To facilitate the technical work, Sub-Committee SC 5 is supported by 11 Working Groups (WGs); WG 1 is responsible for cross-laminated timber. National mirror committees send experts to the working groups. The working groups are responsible for their specific work programs, engaging in technical discussions that lead to proposals for standardization.

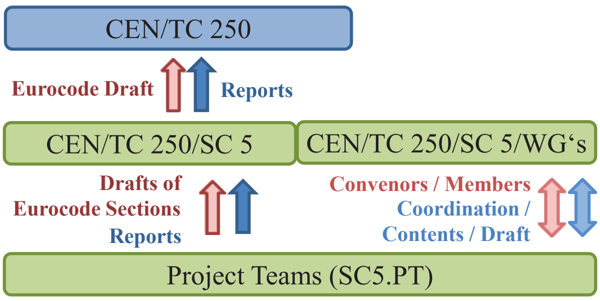

Figure 2 Workflow of standardization

The development of a draft clause, including drawings, is the responsibility of so-called Project Teams (PTs). Within a specified timeframe, the PTs must create a standard draft clause, including harmonized terminology and symbols, considering the principles of "ease-of-use" [7]. Additionally, the PTs must develop background documents that describe the technical justifications and scientific backgrounds for the proposed clauses within the standardization. During the drafting phase, the PTs' drafts go through three phases of commenting by the national standardization committees. The Project Team SC5.T1, responsible for the drafts on the design of *cross-laminated timber* and *reinforcement*, submitted its final drafts at the end of April 2018. The draft on CLT was further discussed, commented on, and adjusted in Working Group WG 1. In October 2021, the two drafts became part of prEN 1995-1-1, the consolidated version of Eurocode 5-1 for the purpose of an internal enquiry in CEN/TC 250/SC 5. After incorporating the comments received during the internal enquiry, the draft document for the official formal enquiry was prepared. The official enquiry on prEN 1995-1-1:2023 was finalized in January 2024. These comments will be discussed and incorporated in the draft version for formal vote until mid-2024. This manuscript presents the most important content and background information of prEN 1995-1-1:2023 for formal enquiry on the subject of *cross-laminated timber*, including changes during the course of standardization work. It also explains the improvements compared to previous application documents.

3. Cross-laminated timber

3.1. Fundamentals of structural design and material properties

General

Due to the orthotropic arrangement of individual layers, the load-bearing behavior of cross-laminated timber elements is characterized by designed orthotropic properties, as illustrated in Figure 3.

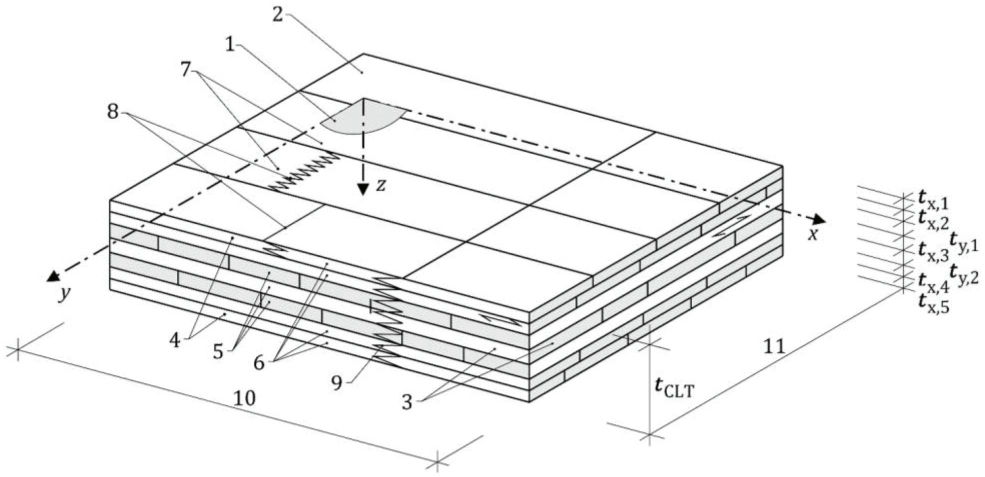

Figure 3 Cross-laminated timber; 1) plane of the member; 2) wide face; 3) narrow face; 4) outer layer; 5) inner layer; 6) parallel outer laminations; 7) lamination; 8) finger joint in lamination; 9) large finger joint; 10) usually the length; 11) usually the width b_{CLT} of a plate or height h_{CLT} of a beam.

For stress and deformation calculations, it is crucial to use correct cross-sectional and stiffness values. In determining normal stresses, only the layers oriented in the direction of stress are considered, while the cross layers are neglected in determining cross-sectional values. However, it is essential to note that these cross layers are subjected to rolling shear. Rolling shear strength is very low. Due to the simultaneously very low rolling shear modulus ($G_{r,mean} \approx 0.15\ G_{mean}$), significantly higher shear deformations occur in the cross layers compared to the longitudinal layers. As a result, the Bernoulli hypothesis of a planar cross-section is no longer fulfilled, and the distribution of bending stresses deviates from the Bernoulli beam theory, as shown in Figure 4.

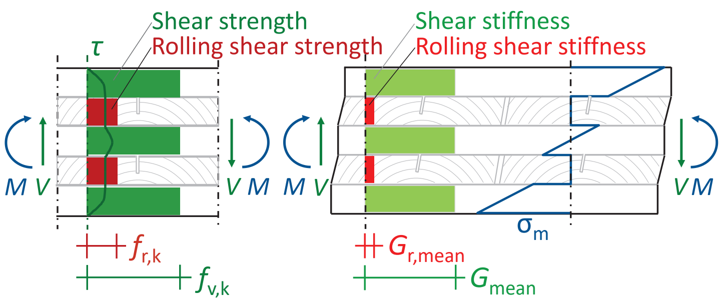

Figure 4 Cross-laminated Timber: distribution of shear and bending stresses, deformation figure, shear strength and shear stiffness subject to layer direction.

In the draft clauses on *Cross-Laminated Timber*, the material is defined as a load-bearing timber product consisting of at least three layers bonded together, always including board laminations but also allowing for wood-based panels. At least one layer is arranged perpendicular to the adjacent layers. The application is limited to service classes 1 and 2.

Partial safety factors, k_{mod}, k_{def}

Despite the specific characteristics of cross-laminated timber that have enabled a broad application of large, solid wood components, some analogies can be drawn in regards to glued laminated timber (GL). Both products typically consist of strength-graded softwood lamellas, bonded with adhesives from the same adhesive families. The minimum requirements for manufacturing, initial testing, and in-house product control are comparable, and the reference test specimens for CLT and GL (according to EN 14080 [9]) have similar dimensions and a similar number of lamellas with the grain parallel to the load direction. This level of similarities justifies [10] why the same partial safety factor is recommended for glued laminated timber and cross-laminated timber:

$$\gamma_M = 1{,}25 \tag{1}$$

The modification factor k_{mod} for cross-laminated timber is also recommended to have identical values as for solid wood and glue-laminated timber, as shown in Tab. 1.

Table 1 Values of k_{mod} for cross-laminated timber

Service class	Load-duration class				
	Permanent	Long-term	Medium term	Short-term	Instantaneous
1	0,6	0,7	0,8	0,9	1,1
2	0,6	0,7	0,8	0,9	1,1

When considering the deformation factors k_{def}, it is essential to take into account that the cross layers of cross-laminated timber are subjected to rolling shear, as illustrated in Figure 4. Significant creep deformation occurs in these layers [11]. Therefore, it is recommended to use the same deformation factors k_{def} as for plywood, as shown in Table 2. These values differ from those in the German National Annex to Eurocode 5 [4].

Table 2 Values of k_{def} for cross-laminated timber

Material	Service-class	
	1	2
Cross-Laminated Timber	0,80	1,00

Strength and stiffness properties

Cross-laminated timber shall be manufactured according to a national product standard, general technical approval or an ETA based on the EAD [13]. The specified strength and stiffness properties typically refer to the properties of the boards of the layers with grain parallel to the direction of the considered stress. The system effects known from abZ/ETAs or [3] shall not be applied; they are already integrated into the underlying strength model. Minor cross-sectional weaknesses resulting from gaps and relief grooves may be disregarded for the verification of the structural member. Table 3 presents a proposal for a strength class CL24. The values given in this table represent lower-bound values of strength and stiffness properties given in current ETAs. Specific ETAs might feature higher single values.

Numerous comprehensive studies have been realized to enable the determination of strength and stiffness properties of a CLT element from the properties of the layers. Such a model might be included in a future revision of EN 16351. Interested readers are referred to [14] as well as the information und literature references in [15].

Table 3 Characteristic strength and stiffness properties and density for cross-laminated timber with layers from solid wood.

Property		Symbol	Unit	CL24
Bending strength	Out of plane loading (slab)	$f_{m,k}$	N/mm²	24
	In plane loading (diaphragm)	$f_{m,edge,k}$	N/mm²	20,5 [a]
Tension strength	In plane loading	$f_{t,0,k}$	N/mm²	14
	Perpendicular to plane loading	$f_{t,90,k}$	N/mm²	0,12
Compressive strength	In plane loading	$f_{c,0,k}$	N/mm²	21,0
	Perpendicular to plane loading	$f_{c,90,k}$	N/mm²	2,5
Shear strength	Out of plane loading	$f_{v,k}$	N/mm²	3,5
	Rolling shear	$f_{r,k}$	N/mm²	0,7
	Perpendicular to plane loading	$f_{v,xy,k}$	N/mm²	5,5 [a]
Modulus of elasticity	In and out of plane loading	E_{mean}	N/mm²	11.000
	Perpendicular to plane loading	$E_{90,mean}$	N/mm²	370
Shear modulus	Out of plane loading	G_{mean}	N/mm²	650
	Rolling shear	$G_{r,mean}$	N/mm²	50
	In-plane loading	$G_{v,xy,mean}$	N/mm²	250
Density		ρ_k	kg/m³	385

[a] This value is usually not declared within DoP. The given value is taken from EN 16351:2021 which is not a harmonized standard. If a different value is declared by the manufacturer, that value applies. National regulations may apply.

For cross-laminated timber elements subjected to out of plane bending (perpendicular loading to the plane) of the panel (including buckling), with widths b_{CLT} smaller than the element thickness t_{CLT}, the strength properties are to be set to zero. For element widths $t_{CLT} \leq b_{CLT} \leq 600$ mm, the bending, tensile, and compressive strengths parallel to the grain should be reduced by $k_{red,b}$:

$$k_{\text{red,b}} = \frac{b_{CLT}[mm]}{1200} + 0{,}5 \qquad (2)$$

For cross-laminated timber elements subjected to in plane bending, system factors (increase factors) are provided for components with more than one layer with grain orientation parallel to the associated stress (a conservative assumption in the strength model) and for component heights 150 mm ≤ h_{CLT} ≤ 600 mm. For cross-laminated timber elements subjected to out of plane bending of the panel, no additional volume factor k_h is specified due to the relatively low number of layers and the associated brittle tensile failure of the outer layers.

The swelling and shrinkage factors of cross-laminated timber made of softwood can be assumed as followed: Perpendicular to the element plane, it is 0.24% per percentage change in wood moisture content, and in the element plane, it is 0.02% - 0.04% per percentage change in wood moisture content. The swelling and shrinking dimensions in plane depend on the layup. For typical structures, the smaller value refers to the x-direction (direction of the outer layers), and the larger value refers to the y-direction

(direction of the cross layers). In some cases, the swelling and shrinking dimensions may be higher [16].

3.2. Ultimate limit state (ULS)

The draft clauses on the design of *Cross-Laminated Timber* do not provide specific information on the application of particular methods for the calculation of cross-laminated timber elements under out-of-plane loading. The choice of analytical calculation approaches (e.g., γ-method [3], shear analogy method [4], Timoshenko) is left to the structural engineer. A comparative overview of applicable methods can be found in [17] and [18].

The stress verifications are to be realized with the effective cross-sections of the layers oriented in the direction of the stresses under consideration, as shown in Figure 5, unless they are explicitly referred to the gross cross-section of the cross-laminated timber element. The designation of the direction of moment loading in Figure 5 deviates from the classical nomenclature according to plate theory. This divergence is necessary to avoid confusion between two different bending stresses (from the bending of the plate or slab), which would otherwise share the same designation.

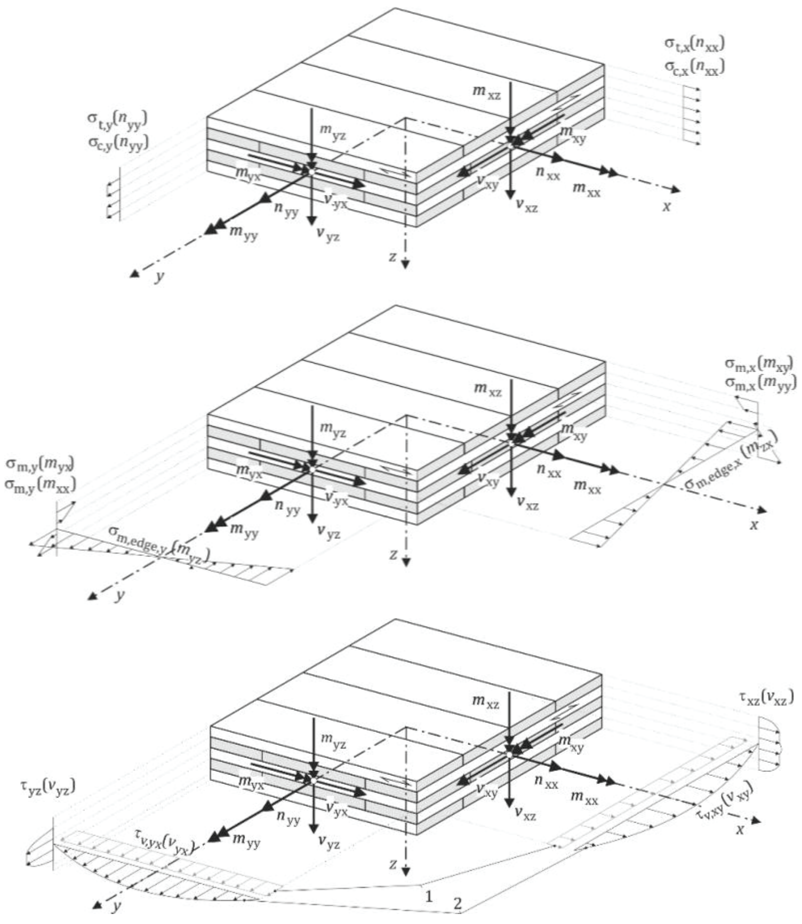

Figure 5 Designation of stresses, forces and moments for an exemplary stress distribution in a cross-laminated timber element (above: normal stresses; middle: bending stresses; below: shear stresses)

Bending

The influence of shear deformation on bending stresses may be neglected for slender single-span beams (ℓ/t_{CLT} or $\ell/h_{CLT} \geq 30$). The bending strengths provided in Table 3 already account for the combination of bending and tensile stresses in the layers, hence verification of bending stresses at the outer edges is sufficient. The need for a combined verification of tension stresses at the center of gravity of the outer laminations and the bending stresses at the outer edges of the CLT panel is omitted, except for stocky cross-laminated timber elements ($\ell/h_{CLT} < 5$) subjected to in-plane bending.

Shear

Depending on the loading conditions, up to five different failure modes in shear need to be considered for cross-laminated timber: shear and rolling shear in the case of out-of-plane loading, as illustrated in Figure 4, as well as gross shear, net shear, and torsional shear at the intersections of two laminations in the case of in-plane loading of the plate, as shown in Figure 6.

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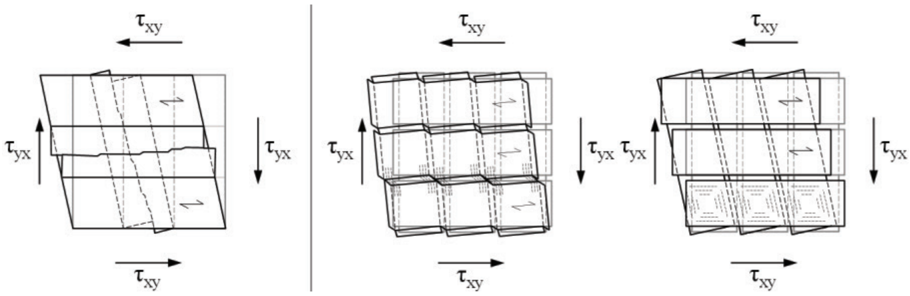

Figure 6 Failure mechanisms gross shear, net shear and torsion, from [20]

In comparison to the information in the general abZ (German national technical approval) and ETAs (European Technical Assessments), the verification methods and strength parameters considered in the *Cross-Laminated Timber Draft* have been harmonized. In cases of out-of-plane loading, the rolling shear stresses are usually governing. Rolling shear is primarily governed by the ratio between lamination width or the distance between gaps/grooves to the layer or lamination thickness, b_l/t_l, see also [19]. The crack factor can be set to $k_{cr} = 1{,}0$. When the CLT plate is subjected to in-plane loading, typically only the verification of net shear (with the associated strength $f_{v,xy,k} = f_{v,yx,k} = 5{,}5$ N/mm^2) is governed. When determining the decisive effective net cross-section (sum of the weaker layers), the thickness t_I of the outer layers shall be reduced by 20%, as outlined in [20]. In-plane loading on net shear of the plate also results in torsional stresses in the intersections between two laminations (and vice versa). The corresponding verification of torsional stresses in the bonded surfaces of orthogonally glued laminations is currently required only for cross-laminated timber elements where the ratio is $b_l/t_l \leq 4$ [21]. In these cases:

$$\tau_{\mathrm{tor,node,d}} = \frac{3}{2} \cdot \tau_{\mathrm{v,xy,d}} \cdot \left(\frac{t_l}{b_l}\right) \leq f_{\mathrm{tor,node,d}} \qquad (3)$$

The properties of cross-laminated timber under gross shear are not considered, as they would require a load-bearing bonding of the narrow edges of the laminations and nearly crack-free performance over the service life of the structure.

The shear design for beams made of cross-laminated timber under in-plane bending (edgewise bending) is also addressed in the draft clauses on the design of *Cross-Laminated Timber*. The design approach closely follows the information provided by Flaig [22].

Stability verification

In the verification for buckling using the equivalent length method, the imperfection factor may be set to $\beta_c = 0.1$, similar to glued laminated timber. In the stress calculation, shear deformations may be neglected, as the risk of buckling increases with higher slenderness, while the influence of shear deformations on bending stresses decreases.

3.3. Serviceability limit state (SLS)

In typical design situations, deformation verifications are usually governing for cross-laminated timber elements supported as single-span beams with spans $\ell < 4$ m, while vibration verifications typically govern for spans $\ell > 4$ m. The share of shear deformation w_V in the total deformation w is typically below 10 % when the span-to-thickness ratio is $\ell/t_{CLT} \geq 30$, in these cases, the additional deformation from shear may be neglected.

Within the framework of vibration verifications according to the currently applicable version of Eurocode 5 [3], verifications of natural frequency, deflection under a single load (stiffness), and acceleration are conducted. Recent developments in floor constructions such as cross-laminated timber and timber-concrete composite constructions are challenging to verify with these criteria (e.g. natural frequency $f_1 > 8$ Hz). Accordingly, the new Eurocode draft also includes *Cross-Laminated Timber* floors (typical heavier floors $g_k \geq 50$ kg/m^3) in the design rules for the vibration verification, also including recommendations of *Hamm* [23]. These suggestions were discussed and further processed in the responsible Project Team SC5.T3 and then incorporated into the consolidated version prEN 1995-1-1:2021. The approach layed out in the current draft document prEN1995-1-1:2023 is shown in Table. 4. Six floor performance levels are given (of which levels I and II are limits typically aimed at for most floor structures). The performance levels are linked to limits of the response factor and the maximum deflection under a single load. Using these elements, verification of natural frequency, minimum stiffness, acceleration and velocity are required. Table 5 provides values for the modal damping ratio of cross-laminated timber floors given in prEN1995-1-1:2023.

Table 4 Floor vibration criteria according to the floor performance level

	Floor performance levels					
Criteria	I	II	III	IV	V	VI
Response factor R	4	8	12	24	36	48
Upper deflection limit $w_{\mathrm{lim,max}}$ in mm	0,25		0,5	1,0	1,5	2,0
Stiffness criteria for all floors	$w_{1\mathrm{kN}} \leq w_{\mathrm{lim}}$ mm					
Frequency criteria for all floors	$f_1 \geq 4{,}5$ Hz					
Acceleration criteria for resonant vibration design situations ($f_1 < f_{1,\mathrm{lim}}$)	$a_{\mathrm{rms}} \leq 0{,}005\, R$ m/s^2					
Velocity criteria for all floors	$v_{\mathrm{rms}} \leq 0{,}0001\, R$ m/s					

Table 5 Values for the modal damping ratio ζ *for cross-laminated timber* floors

Floor lay-up	Modal damping ratio ζ
CLT-floor with floating floor layer	0,04
CLT-floor	0,025

3.4. Members

Wall diaphragms

For cross-laminated timber elements used as wall diaphragms, construction rules are provided, which are given in the following in excerpts. A structural wall diaphragm should have a height-to-width ratio of $h/\ell \leq 4$. Wall diaphragms can be realized as monolithic or segmented wall diaphragms. The connections between parts of a segmented wall can be designed for a constant shear flow. Stresses from horizontal loads in window or door lintels should be considered, if the lifting of adjacent walls is not prevented. When calculating stresses and deformation, the deformation contributions of the connections should be considered. In contrast to the information in general abZ / ETAs, the shear stiffness of a wall diaphragm made of CLT may be determined using the shear modulus for in-plane shear, $G_{xy,mean} = G_{yx,mean}$ and assuming the gross cross-section.

Concentrated loads in plane

When joists or purlins are supported by CLT walls, high loads are locally transferred into the structural element, at the supporting area. Additionally, compression stresses in the contact area, the stability of the member and, if necessary, compression stresses in the member underneath the CLT wall should be verified. Information on the internal load transfer is provided for this purpose, by the new Eurocode draft. For cross-laminated timber elements within the following limits, this information is significantly simplified:

- The ratio of the sum of the layer thicknesses in the direction of the load $\sum t_x$ to the total thickness t_{CLT} is $\sum t_x / t_{CLT} \geq 0{,}75$
- The ratio of the width of the load introduction to the member height h is $b/h \leq 0{,}15$

In these cases, the effective width at half the height of the element $b_{ef}(h/2)$ can simply be calculated assuming a load dispersion angle of 15°. This load dispersion shall only be considered over half of the member height h. In the case of different lengths of load introduction, b_{ef} shall be calculated based on the smaller length.

Compression perpendicular to grain

For cross-laminated timber elements with a ratio between maximum and minimum layer thickness $t_{l,max}/t_{l,min} \leq 2$, the stress spreading factor $k_{c,90,CLT}$ can be calculated as follows:

- $k_{c,90,CLT} = \sqrt{\frac{b_{ef} \cdot l_{ef}}{b \cdot l}} \leq 4$ (4)

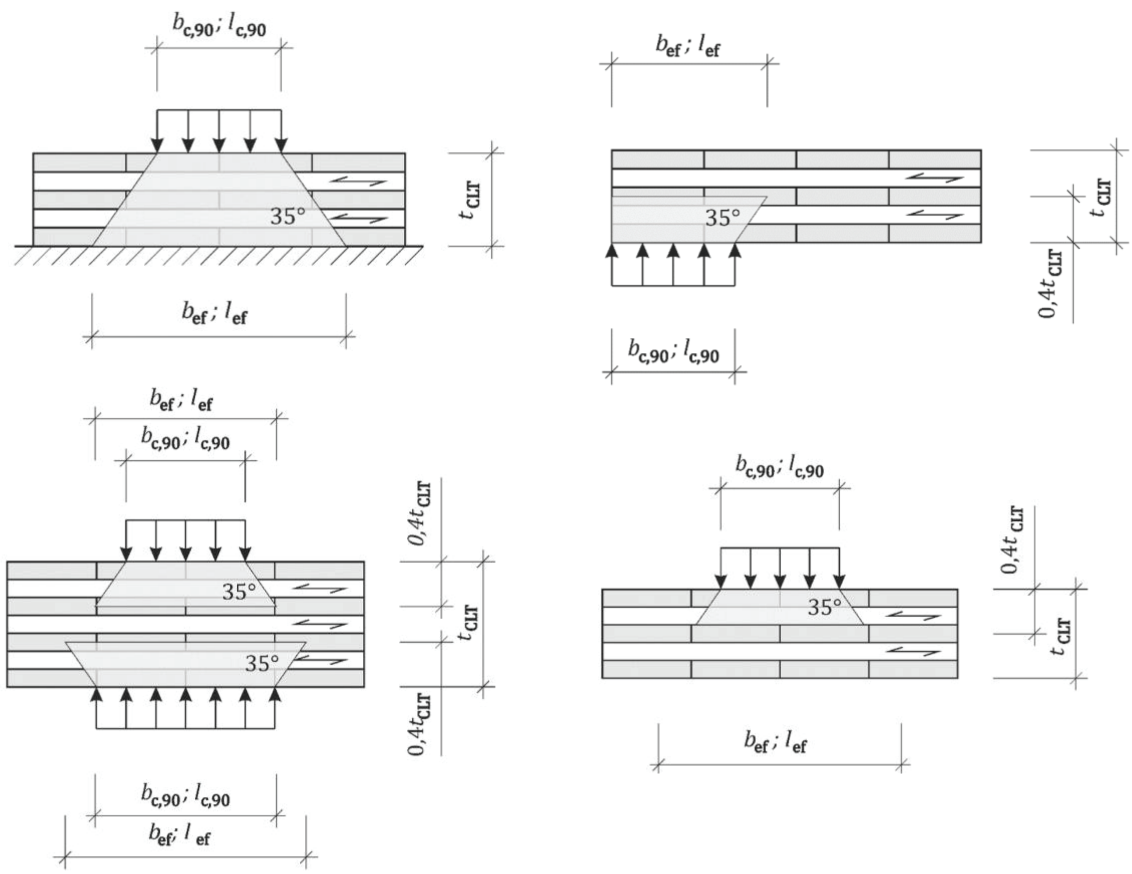

Figure 7 Force distribution width and stress spreading length in CLT subjected to compression perpendicular to the plane

The distribution width b_{ef} or length ℓ_{ef} is based on the assumption of an average stress distribution angle of 35° (longitudinal layers: 45°, transverse layers: 15°), as shown in Figure 7. In many ETAs of CLT products, the compressive strength perpendicular to the grain of CLT made of solid wood laminations is $f_{c,90,k}$ = 3,0 N/mm^2. This is higher compared to glued laminated timber. The same applies to the elastic modulus perpendicular to the grain. In both cases, this is due to the restraining effect of the cross layers [24].

Concentrated loads perpendicular to plane

For the "punching shear verification" under concentrated loads perpendicular to the plane of cross-laminated timber panels, the governing factor is usually the rolling shear strength. This situation usually applies for point supported CLT floor elements. Due to a positively acting stress interaction from compression perpendicular to the grain and rolling shear, as well as nonlinear effects in the area of load concentration [25], for cross-laminated timber consisting exclusively of solid wood layers, a 60% higher rolling shear strength can be assumed [26]. Therefore, a verification of rolling shear stresses, applying an increase factor $k_{r,pu}$, has to be conducted. The rolling shear stresses in the area of concentrated loads may be determined by assuming an effective width. For this purpose, a perimeter under an angle of 35° up to the decisive location can be assumed, as shown in Figure 8 and [25].

The verification is then to be carried out as follows:

$$\tau_{r,d} \leq k_{r,pu} \cdot f_{r,d} \tag{5}$$

with: $k_{r,pu}$ = 1,60 for CLT exclusively made of timber layers

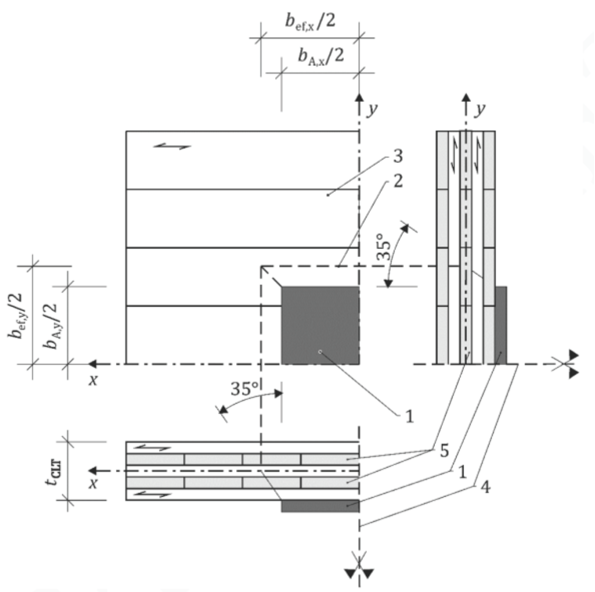

Figure 8 CLT under concentrated load (1 – area of load introduction; 2 – perimeter for stress verification; 3 – CLT; 4 – member edge or axis of symmetry; 5 – decisive layer)

Reinforcement to cover high support loads or high point loads are also addressed in the draft clauses on the design of *Cross-Laminated Timber*. The design approach closely follows the information provided by *Mestek* [25].

Ribbed plates

The draft for Cross-Laminated Timber (CLT) also includes information on the design of ribbed panels made from CLT panels, bonded with, for example, a glued laminated timber cross-section.

4. Acknowledgements

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6. Appendix

G_{mean} *mean shear modulus;*

$G_{r,mean}$ *mean rolling shear modulus;*

b_{ef} *effective width;*

$f_{r,d}$ *design rolling shear strength*

$f_{tor,node,k}$ *characteristic torsional shear strength of the glued area of crosswise bonded lamellae;*

$k_{r,pu}$ *factor to account for the non-linear behaviour and the strength combination;*

$k_{red,b}$ *factor for reduced width of CLT members;*

$k_{c,90,CLT}$ *stress spreading factor accounting for the distribution of compressive stresses in the member and the layup of the CLT element*

ℓ_{ef} *spreading length;*

$t_{l,min}$ *minimum lamination thickness within a layup;*

$t_{l,max}$ *maximum lamination thickness within a layup;*

t_x *sum of thicknesses of layers in x-direction;*

β_c *imperfection factor for flexural buckling about y- or z-axis;*

ζ *modal damping ratio;*

$\tau_{r,d}$ *design rolling shear stress;*

$\tau_{tor,node,d}$ *design torsional shear stress of glued area of crosswise bonded lamellae.*

Design for serviceability limit state – case floor vibration

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Abstract

This paper describes the backgrounds of the floor vibration design method introduced to the draft of the new Eurocode 5 draft. As compared to the present Eurocode 5 method, several new possibilities are introduced. Different floor performance levels are introduced which reflect different floor vibration response. How these are actually used in practice is a nationally determined parameter, but a recommendation is given for residential and office use categories. The design equations are not presented here, they can be found from the Eurocode draft. The calculation of two typical floor sructures are presented at the end of this paper.

Key words: Floor, vibration, serviceability, damping, frequency, deflection, velocity, acceleration.

1 Introduction

This paper describes the content of the next generation Eurocode on the design of floor vibrations. Note that as the draft has recently been on a formal enquiry and comments have been received, the draft is not yet fully stable. So changes and modifications to the draft are very likely.

The content described in this paper has been carried out in the standardisation body CEN/TC250/SC5/WG3/SG4, which is a sub-group with the task to produce the clauses for the design of floor vibration. This paper is based on the yet unpublished background paper to the draft.

The general framework of the clauses of the current Eurocode 5 are followed in the new draft. However, major changes and extensions to the design rules are also introduced. These are based on a large number of research projects and Phds that have been carried out during the last 30 years in many countries including Austria, Canada, Germany, Finland, Sweden, Norway and the UK. A recent JRC European Commission report (Sedlacek et al. 2009) describes the results of an EU project on steel floors, this is utilised for comparison as well. The background on the draft clauses is based on the reference list given at the end of this document.

In the following, the major differences to the current Eurocode are introduced together with the appropriate reference stating the background to the proposed change.

invited, contributed oral lectures as well as for posters). Please follow the requested format of the abstract template. Papers and oral presentations should be written in correct British English. The editors are not expected to do any reformatting to the final papers. In addition, papers should not include any kind of commercialism.

2 Design for vibration

2.1 General

Currently, the damping ratio of timber floors, unless other values are proven to be more appropriate, is be assumed to be as $\zeta = 0{,}01$ or (1%) of the critical damping.

During the past over ten years, a significant number of floor vibration studies have been carried out in Europe and worldwide. From these studies, it has been found that in modern floors, the damping is significantly higher than what has been assumed (Hamm et al.

2010, Homb et al. 2018, Järnerö 2014, Sedlacek 2009, Smith et al 2009, Toratti et al 2006, Weckendorf 2015, Willford et al 2006, Winter et al 2010, Zhang et al 2013, Zimmer et al. 2016). This may be due to structural damping as the floors are generally composed of many layers and the end conditions are not freely supported. It has also been noted that on-site testing gives much higher damping that in freely supported laboratory conditions.

ISO 10137-2007 (annex B) gives typical ranges of damping values for different floor types. For timber floors a recommended range between 0,015 – 0,04 is given. An extreme range would be 0,01 – 0,055 and for preliminary design, a suggested value of a bare floor is 0,02.

The JRC report (Sedlacek et al. 2009) proposed a damping ratio of 0,06 for timber floors, which is considerably higher than what was proposed for steel and concrete floors. This value is considered here to be too high to be used as a general value for all timber floors.

For these reasons, in this draft, the modal damping ratio applied to the first mode, which has usually the highest energy, may be conservatively assumed as:

- ζ = 0,02 for joisted floors
- ζ = 0,025 for timber-concrete, rib type and slab type (e.g., CLT, LVL) floors
- ζ = 0,03 for joisted floors with a floating layer
- ζ = 0,04 for timber-concrete, rib type and slab type (e.g., CLT, LVL) floors with a floating layer

The damping values can alternatively be obtained for different floor configurations by on-site testing applying the new floor vibration test method standard EN 16929-2018 Test methods - Timber floors - Determination of vibration properties.

The consideration of 4 side supported floors has been discussed in WG3/SG4 several times. It has been concluded that in practice (almost) all floors are 4 side supported even in cases of minimal transverse floor stiffness. The first mode shapes are decisive and in practice, the sides of floors do not deflect or vibrate. Bridge-type floors are a different case, but these are rare and therefore 4-side supporting is not mentioned anymore in the final draft.

2.2 Vibrations from machinery

No distinct design rules for vibrations induced from machinery are given here. The general clauses from the existing Eurocode are kept unchanged. The only addition here is that it is generally stated that for vibrations induced by traffic loads and crowd loading, a more detailed investigation which accurately models the loads and modal properties of the structure should be performed.

2.3 Vibrations from footfall

From here on, there are significant changes in this draft as compared to the existing Eurocode.

The existing Eurocode considers only the residential use category and gives a design procedure only for floors with a fundamental frequency above 8 Hz.

Here also other use categories assumed to be of similar nature as to floor vibrations (Categories of use A, B, C1, C3 Cand D as defined in [EN 1991-1-1]) are included. These use categories include residential floors, office floors and areas with moderate amount of people like museums, exposition rooms etc. as well as access areas in offices. Categories confined to crowd loading such as theatres, gymnastic halls, dance halls and areas with sensitive equipment are excluded.

In this draft, the floor fundamental frequency shall in all cases be above 4,5 Hz.

In early stages of drafting, it was assumed that if the floor has a fundamental frequency of 4,5 Hz < $f_{1,\mathrm{lim}}$ < 8 Hz, the floors is termed as a resonant floor, and when this is $f_{1,\mathrm{lim}} \geq$ 8 Hz, the floor is termed as a transient floor. This division is normally applied in literature.

In later stages of drafting, it was decided also to consider the walking frequency as follows:

The fundamental frequency limit above which resonant response will not occur $f_{1,lim}$ should be taken as the larger of: four times the walking frequency and 8 Hz in cases of floor performance levels I-V or 7 Hz in case of floor performance level VI (floor performance levels as given in Table 9.1).

The following note was added for explanation: The dynamic loading due to a person walking can be idealised as a periodic function which has 4 significant harmonics. Each harmonic has a frequency equal to the walking frequency multiplied by 1 to 4. For example, the 4th harmonic of a 2 Hz walk will have a frequency of 8 Hz. Resonant response is therefore only possible for floors which have a fundamental frequency lower than or equal to 4 times the walking frequency. For floors with a fundamental frequency greater than 4 times the walking frequency, the resulting dynamic loading can be idealised as a series of impulses with the floor vibration dying out completely between impulses leading to a transient response.

The limit of 7 Hz on floor performance level VI floors was a compromise to member states which do not have very high criteria on floor vibration performance.

Resonant and transient floors have differing design procedures. These follow the footfall induced vibration calculation methods presented (Willford et al. 2006), which is also similar to the methods (Sedlacke et al. 2009 and Smith et al. 2009). Actually, the methods introduced in this draft are not new, these have been used for floor vibration design by specialised experts for some time. The method is introduced in detail in the INTER paper 51-20-2 (Abeysekera et al. 2018). Further Comparisons of measured vibration data to suggested design were carried out in a following INTER paper (Hamm et al. 2020).

Floors stiffness has to be verified for all floor fundamental frequencies, this has been applied for instance in Germany. Transient response should also be checked for all fundamental frequencies. Resonant response should be checked only for floors with a fundamental frequency below $f_{1,lim}$.

It has been emphasised that the floor mass is a unique value of the particular floor and this same mass should be used in the all the various analyses.

Some simple procedures to account for openings in floors have been included. This is merely based on engineering judgement within the working group.

3 Fundamental frequency

The fundamental frequency of the floors may be calculated using two methods: - the classical beam theory, and – based on the deflection caused by a self-weight of the floor. In principle, both will give the same result, but in the later. Factors to consider crosswise bending stiffness and continuous double span floors are also given (Zimmer et al. 2016). These procedures are often given in relevant textbooks and can also be found in ref. (Sedlacek et al. 2009, Smith et al 2009, Wilford et al. 2006).

The floor mass to consider in the calculation of the fundamental frequency as well as on the modal mass of the floor is to include the permanent load and a 10 % portion of the imposed loads. This is a value widely recommended for light-weight floors in the literature (Sedlacek et el. 2009 and Smith et al. 2009).

Imposed loads cover movable equipment (such as furniture) as well as the self-weight of the human occupancy.

For a floor supported elastically on a beam on one or both sides, the resulting fundamental frequency may be calculated with a formula which is based on ref. (Winter et al. 2010) and it can readily be proved analytically.

4 Stiffness, velocity and acceleration criteria

4.1 General

Relating to the stiffness criterion, the background to effective width Formulae 9.17 and 9.18 are given in (Marcroft 2019), where extensive testing is behind. The new Formula gives about 5 % higher effective width values than the old Formula used by many member states national annexes. In addition, there is a special case, which is frequently applied, with a discrete bending member mechanically connected to the floor joists at midspan. This can be calculated with Formula 9.19 and the reference for this is (Marcroft 2019).

The floor criteria are composed of:

- a stiffness criterion based on the deflection caused by a 1 kN point load,
- a velocity criterion, based on the root-mean-square value of a 70 kg walker,
- an acceleration criterion, based on the root-mean-square value similarly of a 70 kg walker.

The calculation scheme for velocity and acceleration is based on the method introduced by Willford M., Young P. (2006).

4.2 Floor performance levels and vibration criteria

Six different floor performance levels (levels I, II, III, IV, V and VI) with respective floor vibration criteria have been introduced shown in Table 9.1. It is intended that for different use categories, the floor performance level will either be specified in national annexes or dictated by the client or the structural designer. Sensitivity to floor vibration is highly subjective. This can be seen by the many ways in which the current rules in EC5 are applied in different European countries. Related to the Cost Action FP0702, a summary of differences in regulations related to floor vibration design is given across Europe (Zang et al. 2013).

The root mean square acceleration or velocity responses are compared to the vibration perception base curve in Figure C.1 of annex C in ISO 10137-2007. The acceleration and velocity criteria are expressed as a multiple of the base curve value. This multiple is termed as the response factor R given in [Table 9.1].

- Six different floor performance level are offered. This is needed to account for the wide cultural variations and respective regulations in the different member states.
- For low frequency floors there is an acceleration criterion a_{rms}.
- For all floors there is a velocity criterion v_{rms}.
- For all floors there is a 1 kN point load stiffness criterion; this is empirical based on historic practice and is particularly useful for light joisted floors.
- The easiest way to compare how current national annexes compare to the performance classes is to check on the 1 kN stiffness criteria given. However, because the point load criterion ignores the mass of the floor it is not a perfect measure and is only applicable to the traditional floor types on which it was developed.
- JRC report (Sedlacek et al. 2009) recommends response factors for residential and office use between 8 and 32 (Class C). This is within the performance level range given in Table 1.

The values of the R-factors and their relation to the point load deflection values have been based on the range obtained from currently used floor structures where experience shows acceptable performance. Such floors are of floor performance levels II and III only, and even here, it is far from being a complete survey of floors throughout Europe. For floor performance levels IV to VI the R-factor values are not certain, however it is known the relation of acceptability to acceleration is logarithmic and this is used as a basis on defining the values. Further adjustments might be needed as more experience is gained.

Figures and tables should be numbered consecutively. Add figure number and caption below each figure, and table number and caption above each table. Figure and table captions should be aligned to the left and the font should be Verdana 10 pt (Style Caption).

Spacing between body text and caption should be 9 pt and between caption and table or figure 3 pt. These spaces are included in the Caption styles. In tables should be used Verdana 10 pt, and in text, which is inside/ inserted on figures Verdana 9 pt. Use only horizontal lines as table borders, like presented below (Table 1).

Table 1 Floor vibration criteria according to floor performance level

	Floor performance levels					
Criteria	**I**	**II**	**III**	**IV**	**V**	**VI**
Response factor R	4	8	12	(24)*	(36)*	(48)*
Upper deflection limit $w_{\text{lim,max}}$ in mm	0,25	0,25	0,5	1,0	1,5	2,0
Stiffness criteria for all floors	$w_{1\text{kN}} \leq w_{\text{lim}}$ mm					
Frequency criteria for all floors	$f_1 \geq 4{,}5$ Hz					
Acceleration criteria for resonant vibration design situations ($f_1 < f_{1,\text{lim}}$)	$a_{\text{rms}} \leq 0{,}005$ R m/s^2					
Velocity criteria for all floors	$v_{\text{rms}} \leq 0{,}0001$ R m/s					

* These values will most probably be changed

Table 2 Recommended selection of floor performance levels for use categories A (residential) and B (office)

Use category	Quality choice	Base choice	Economy choice
A (residential)			
multi-family block	level I, II, III	level IV	level V
single family house	level I, II, III, IV	level V	level VI
B (office)	level I, II, III	level IV	level V

NOTE 1 The recommendation is divided into a base, quality or economy choices depending on which aspect has more emphasis.

NOTE 2 For the different building use categories, the assignment of floor performance levels to be applied, can be stated in the National annex for use in a country.

4.3 Comparison of proposed design method on existing floors

Most of the existing test data on the vibration performance of timber floors is for the transient floor type, as timber floors tend to have a high fundamental frequency. This is necessary for light-weight floors in order to be acceptable by the users and to avoid resonances.

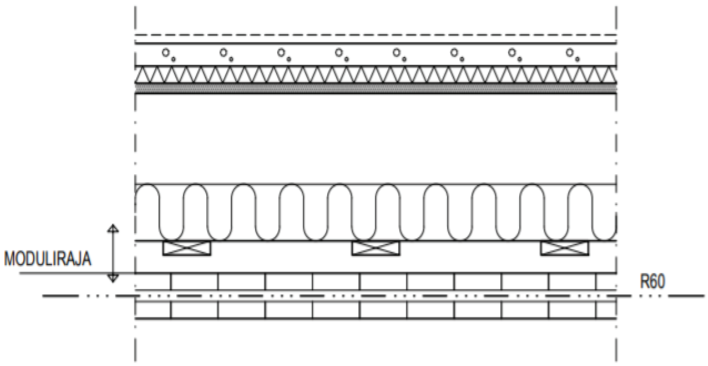
Resonant floors need to be of medium to heavy-weight in order to be acceptable (and to fulfil the acceleration criterion). Such floors should not develop resonances from human excitation. For these floors, there is not as much experience in timber construction as these have not been previously included in Eurocode 5. Such floors will need heavy layers such as for instance concrete (e.g. in timber-concrete composite floors)

Some example calculations are given in the following annex. The two transient floor examples are very typical currently. The calculation shows their standing in the floor performance level scale.

Annex A Example calculations of timber floors using the floor vibration design methods

The calculations below show how the methods of the Eurocode 5 draft apply on two typical transient floors. These examples show how the floors would be classified.

1. Transient Floor 1



<u>Floor composition:</u>
40 mm screed
30 mm Impact sound insulation
18 mm OSB panel
260 mm Kerto-S span 5500 mm width 12000 mm, 51x260 K300 mm
100 mm soft insulation and supporting boards 25x100 K400 mm
Floor area 5,5 x 12 m^2

(lower element is a CLT roof which is not part of the floor structure as this is a section of a module element)

$$EI_L = 3{,}54 \cdot 10^{12} \, [\frac{Nmm^2}{m}]$$
$$EI_T = 9{,}93 \cdot 10^{10} \, [\frac{Nmm^2}{m}]$$
$$Floor\ mass: m = 111 + 200 * 0{,}1 = 131 \, [kg/m^2]$$

<u>Fundamental frequency:</u>

Deflection from self-weight $w_{sys} = 4{,}42 \, [mm]$

$$f_1 = k_{e,2} \frac{18}{\sqrt{w_{sys}}} \quad [\text{Hz}]$$

***f*₁ = 8,6 [Hz]**

<u>Stiffness criterion</u>

5 $$Bb_{eff} = 0{,}95 \, l \sqrt[4]{\frac{EI_T}{EI_L}} = 2{,}14 \; [m]$$

$$w_{1KN} = \frac{F \cdot l^3}{48(EI)_L\, B_{eff}} = \frac{1000 \cdot 5500^3}{48 \cdot 3{,}54 \cdot 10^{12} \cdot 2{,}04} = \mathbf{0{,}458}\ [\boldsymbol{mm}]$$

This results to floor performance level LEVEL III

<u>Velocity criterion (1,5 Hz walking)</u>

$$f_w = 1.5\ [Hz]$$

$$I = \frac{42\, f_w^{1.43}}{f_1^{1.3}} = \frac{42 \cdot 1.5^{1.43}}{8{,}6^{1.3}} = 4{,}57\ [Ns]$$
$$M^* = \frac{mlb}{4} = 2161\ [kg]$$
$$v_{1,peak} = kred\, \frac{I}{(M^* + 70)} = 0{,}0014\ \left[\frac{m}{s}\right]$$

$$K_{imp} = 0.48 \cdot \frac{b}{l} \cdot \left(\frac{EI_L}{EI_T}\right)^{0.25} = 2{,}59$$

$$v_{tot,peak} = K_{imp} \cdot v_{1,peak} = 0{,}0037\ \left[\frac{m}{s}\right]$$

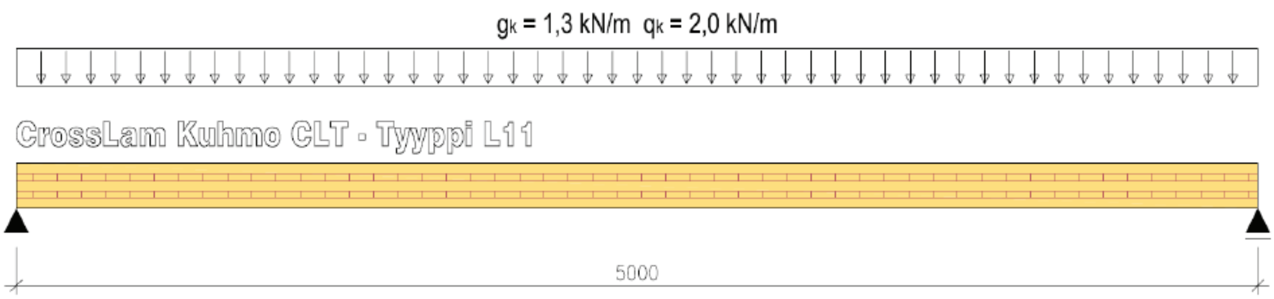
$$\eta = 0{,}69$$
$$\xi = 0.04$$
$$\beta = (0.65 - 0.01 \cdot f_1)(1.22 - 0.11\xi)\eta = 0{,}303$$

$$v_{rms} = \beta\, v_{tot,peak} = 0{,}0011\ \left[\frac{m}{s}\right]$$
$$Response\ level\ R = \frac{V_{rms}}{0.0001} = 11$$

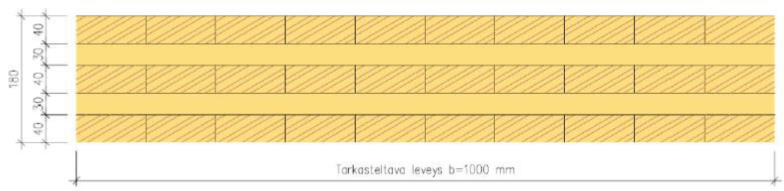
This results to floor performance level LEVEL III

2. Transient Floor 2

A typical CLT Floor having an area of 5 x 5 m^2 (This may be of CLT elements connected in parallel together and considered as a single body).



Cross section



<u>Moment of inertia in span direction</u>

$$EI_L = 4{,}72 \cdot 10^{12}\ \frac{Nmm^2}{m}$$

$EI_T = 1{,}05 \cdot 10^{12} \ \frac{Nmm^2}{m}$

$Floor\ mass: m = 130 + 200 \cdot 0{,}1 = 150\ kg/m^2$

Fundamental frequency:

Deflection from self-weight $w_{sys} = 2{,}59\ [mm]$

$f_1 = k_{e,2} \frac{18}{\sqrt{w_{sys}}}$ [Hz]

***f₁* = 12,3 [Hz]**

Stiffness criterion

6 $b_{eff} = 0{,}95 l \sqrt[4]{\frac{EI_T}{EI_L}} = 3{,}26\ m$

$w_{1KN} = \frac{F \cdot L^3}{48(EI)_L b_{eff}} = \frac{1000 \cdot 5000^3}{48 \cdot 4.72 \cdot 10^{12} \cdot 3{,}26} = \mathbf{0{,}17\ [mm]}$

This results to floor performance level LEVEL I or II

Velocity criterion (1,5 Hz walking)

$f_w = 1.5\ [Hz]$

$I = \frac{42\ f_w^{1.43}}{f_1^{1.3}} = \frac{42 \cdot 1.5^{1.43}}{11{,}6^{1.3}} = 2{,}92\ [Ns]$

$M^* = \frac{mbl}{4} = 937\ [kg]$

$v_{1,peak} = kred \frac{I}{(M^*+70)} = 0.0020\ [\frac{m}{s}]$

$K_{imp} = 0.48 \cdot \frac{b}{l} \cdot \left(\frac{EI_L}{EI_T}\right)^{0.25} = 0.70$

Therefore $K_{imp} = 1$

$v_{tot,peak} = K_{imp} \cdot v_{1,peak} = 0.0020\ [\frac{m}{s}]$

$\eta = 1.52 - 0.55 = 0.97$

$\xi = 0.04$

$\beta = (0.65 - 0.01 \cdot f_1)(1.22 - 0.11\xi)\eta = 0.400$

$v_{rms} = \beta\ v_{tot,peak} = 0.00081\ [\frac{m}{s}]$

$Response\ level = \frac{V_{rms}}{0.0001} = 8{,}1$

This results to floor performance level LEVEL III, actually at a borderline to level II .

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Design of connections

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Abstract

Within the past couple of years, the Eurocode 5 has been reviewed and also the chapter "Connections" was redrafted and updated. The content in the 2004 edition of Eurocode 5 was updated regarding harmonisation, reduction of number of National Determined Parameters (NDP's), simplification, effective material usage (positive effect on climate change) and safety. A special focus was put to the ease of use while new design rules and new material parameters were integrated into the chapter. The new content includes design rules for bonded-in rods, brittle failure modes such as row shear, shear plug and block shear as well as modern carpentry connections, and others. In this paper an overview and insight in the developments of the new chapter "Connections" in Eurocode 5 is be given.

Key words: Connections, Joints, Fasteners, Standardisation, Design Codes, Eurocode 5.

1 Introduction

Within the project to review and update Eurocode 5 chapter "Connections", the CEN committee TC250/SC5 has installed Working Group 5, where the different European countries are represented, and technical discussions are carried out. A Project Team SC5.T5, which was formed from the authors of [1], has drafted the main content of the Connections chapter of prEN 1995-1-1:2023 [2]. Based on the existing content in the 2004 edition of Eurocode 5 [3] the Project Team worked towards harmonisation, reduction of number of National Determined Parameters (NDP's), simplification, effective material usage (positive effect on climate change) and safety. The following, more specific tasks were given in addition:

- Reduction in number of National Choices (NDPs)
- Enhanced ease of use
- Bonded in rods
- Redraft design rules with non-continuous (i.e. –stepped) output
- Row shear, shear plug and block shear
- Design rules for modern carpentry connections
- Connection geometry (spacing, end-, edge distances, etc.)
- Lateral load-carrying capacity, European-yield-model (EYM)
- Fatigue

The completion of the specified tasks forms the basis for the updated chapter "Connections" in Eurocode 5 (see also Figure 1). In addition, the general development of connection technology and new typologies of connections and fasteners were implemented into the new chapter. In contrast with the 2004 version of the Eurocode 5 new clauses are accompanied by background documentation.

In addition to the specific tasks described above, handled by the Project Team, Working Group 5 in CEN TC250/ SC5 included the latest development and state-of-the-art in connection technology in the revision of the Eurocode 5, such as Modern fasteners such as self-tapping screws, Connections with inclined fasteners (screws), Connections with interlayers, Design assisted by testing, and others.

2 Overview of the connections chapter

2.1 General

Easy design of connections is essential for increasing the use of timber structures and thereby take advantage of the low environmental impact. Presently section 8 of the 2004 edition of EN 1995-1-1 "Connection with metal fasteners" only covers a few of the combinations of fastener types and wood products used in practise. There are also non-physical jumps in the design rules. To facilitate the ease of use the clauses in the updated chapter "Connections" in Eurocode 5, are restructured.

The new structure allows an easier understanding of the design of connections also by engineers not working with timber structure on a daily routine. The new structure as well as other proposals for the update of EC5 were developed within the work of COST Action FP1402 [4].

One of the challenges in this restructuring was the question of the size and page count of the revised version of Eurocode 5. Due to the large amount of new topics, approaches, and technologies, the size of the new EC5 increased considerably compared to the previous version. The relative size of the different chapters of prEN 1995-1-1:2023 are shown in Figure 1.

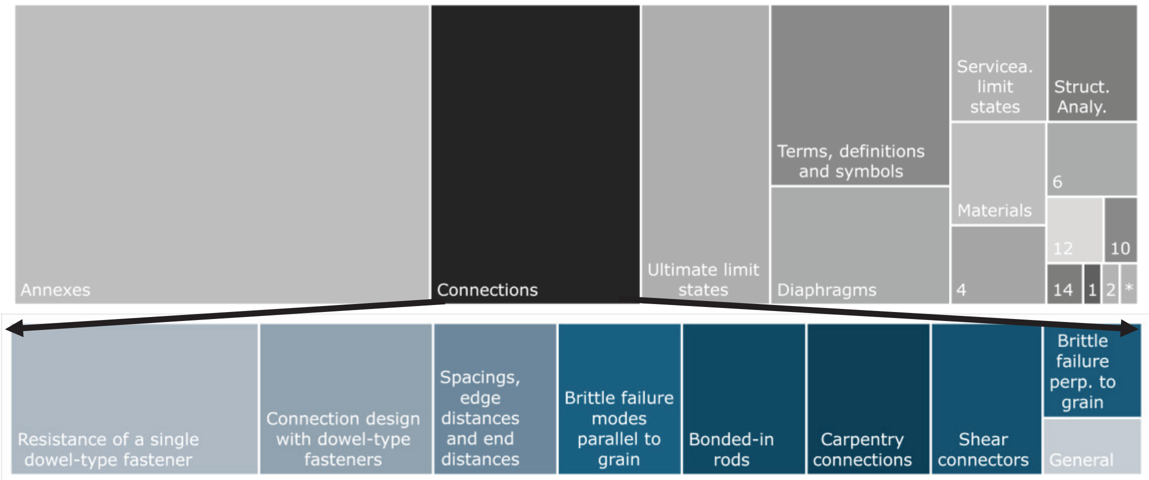

Figure 1 Content and amount of prEN 1995-1-1:2023 and Chapter 11: Connections. Legend: 1 Scope, 2 Normative references, 4 Basis of design, 6 Durability, 10 Fatigue, 12 Mechanically jointed and glued webbed or flanged beams, 14 Timber foundation piles, * Bibliography

Some details on the content of the chapter Connections of the new Eurocode 5 is presented in the following.

2.2 Axial resistance of a fastener

Modern fasteners such as self-tapping screws show highest performance when loaded in axial direction. For the axial resistance three different failure modes are distinguished:

- Head pull-through resistance $F_{pull,k}$ of the fastener head on the timber surface
- Withdrawal resistance $F_{w,k}$ of the thread of the fastener in the timber member
- Tensile resistance $F_{t,k}$ of the fastener itself.

The design axial tensile resistance $F_{ax,t,d}$ of a connection with axially-loaded fasteners can be written as follows:

$$F_{ax,t,d} = n_{ef} \min \begin{cases} \frac{k_{mod}}{\gamma_R} \max \begin{cases} F_{pull,k} \\ F_{w,k} \end{cases} \\ \frac{F_{t,k}}{\gamma_{M2}} \end{cases} \tag{1}$$

The two first failure modes describe failure in the timber whereas the third failure mode describes a pure steel failure. The corresponding partial factors γ_R and γ_{M2} are applied accordingly. In a connection between two timber members, the head pull-through and withdrawal resistance has to be checked in both members and the tensile resistance of the fasteners has to be satisfied. In case the fasteners exhibit both head pull-through and withdrawal resistance in one member, the higher of the two may be used for the design. For partially threaded screws or screws with double thread and without head, of course only the respective resistance is used directly. The effective number of fasteners n_{ef} in the connection depends amongst others on the insertion angle, type of connection, and the number of the fasteners in the group.

For the determination of withdrawal resistance, the former withdrawal parameter f_{ax}, which is related to the withdrawal length and diameter of the fastener, was replaced by a new withdrawal strength f_w, which is based on the withdrawal length and circumferences of the fastener. This new withdrawal strength f_w is now a real "strength" based on the cylindric circumference area of the thread and not only a parameter. This new definition creates a ratio of π between the old withdrawal parameter and the new withdrawal strength. However, it is considered as a more general and consistent expression which is applicable to all dowel-type fasteners according to EN 14592 as well as to bonded-in rods and large diameter screws and threaded rods. In addition, it is in line with the general us of small letter f for strength values instead of parameters.

The values of withdrawal strength for the calculation of the withdrawal resistance and the formulas for the calculation of head-pull-through resistance are given in clear tables for the different fasteners and material combinations. New materials such as CLT were added, and values are updated to most recent knowledge. This allows a quicker design and direct comparison of different fastener types and material performances, and also the addition of parameters for new products.

2.3 Lateral resistance of a fastener

2.3.1 General

One aspect that was criticized by engineers in a survey on their satisfaction with EC5 [4] is the complexity of the existing equations for the determination of the dowel-type fastener capacity in EC5. These equations commonly referred to as the European Yield Model (EYM) are the basis for the design of connections in all types of layout as timber-to-timber or steel-to-timber in single or double shear. In the updated chapter the equations of the EYM were revised and simplified in order to reduce the number of different cases to consider in the different layouts. This resulted in only a single set of equations which means a considerable reduction in length and complexity of the chapter. In addition to this reduction the ease of navigation and guidance for an optimal design of connection is achieved by giving equations for recommended thicknesses in order to achieve the desired beneficial failure modes.

The lateral resistance $F_{v,k}$ of a dowel-type fastener is established by a dowel-effect contribution $F_{D,k}$ and a contribution from the rope-effect $F_{rp,k}$ as specified in Equation (2). In the so-called European Yield Model (EYM) in the 2004 version of Eurocode 5 both these contributions are merged into the same equation. In the new chapter for the revised Eurocode 5 the dowel-effect contribution and the rope-effect contribution are distinguished more clearly and calculated separately. The rope effect contribution may be considered for the failure modes with an inclination of the fastener or when hinges develop in the fastener. However, it must not be considered in the failure modes with pure embedment failure of the fastener in the timber.

$$F_{v,k} = F_{D,k} + F_{rp,k} \tag{2}$$

2.3.2 Dowel-effect contribution of a fastener in single shear

Instead of distinguishing a variety of different configurations of timber-to-timber and steel-to-timber connections, in the new chapter it was focussed on the clear definition of the basic formulas and an explanation and definition of parameters for a more universal use. For a connection between two members with a fastener in single shear, the 6 well known failure modes can be defined as shown in Figure 2 (top). The equation for the determination of the load-carrying capacity is the same as for timber-to-timber (or wood-based panel) in the 2004 version of Eurocode 5. For connections with fasteners in double shear the resistance can be determined from the same formula by omitting the failure modes that cannot develop in this configuration as shown in Figure 2 (bottom).

There are several advantages of the new formulation of the EYM approach and by using only the very general equation. One of them is that only one set of formulae are necessary to cover all combinations for one, two, or even multiple shear planes. The new approach is applicable for a wide range of materials used in modern connections, such as softwood and hardwood materials, panels made of Engineered wood products, aluminium, high strength steel, and others. When being able to define the embedment strength for all these materials, the resistance for connections between members made of all these materials can be determined. This applies also to connections between timber and steel members, by considering a sufficiently high embedment strength of the steel plate. For steel plates the embedment strength is typically three times the yield strength and hence, the assumption of an embedment strength of 600 MPa is adequate. This way, the possible embedment failure modes in the steel plate is directly considered, which is particularly important for internal steel plates.

With the new formulation the differentiation of "thin" or "thick" steel plate is automatically considered and can be evaluated in detail, that means whether the fastener rotates in the respective member or not. Extreme combinations of material parameters can be chosen e.g. for aluminium plates and high-grade steel dowels or high strength steel plates and low-grade fasteners.

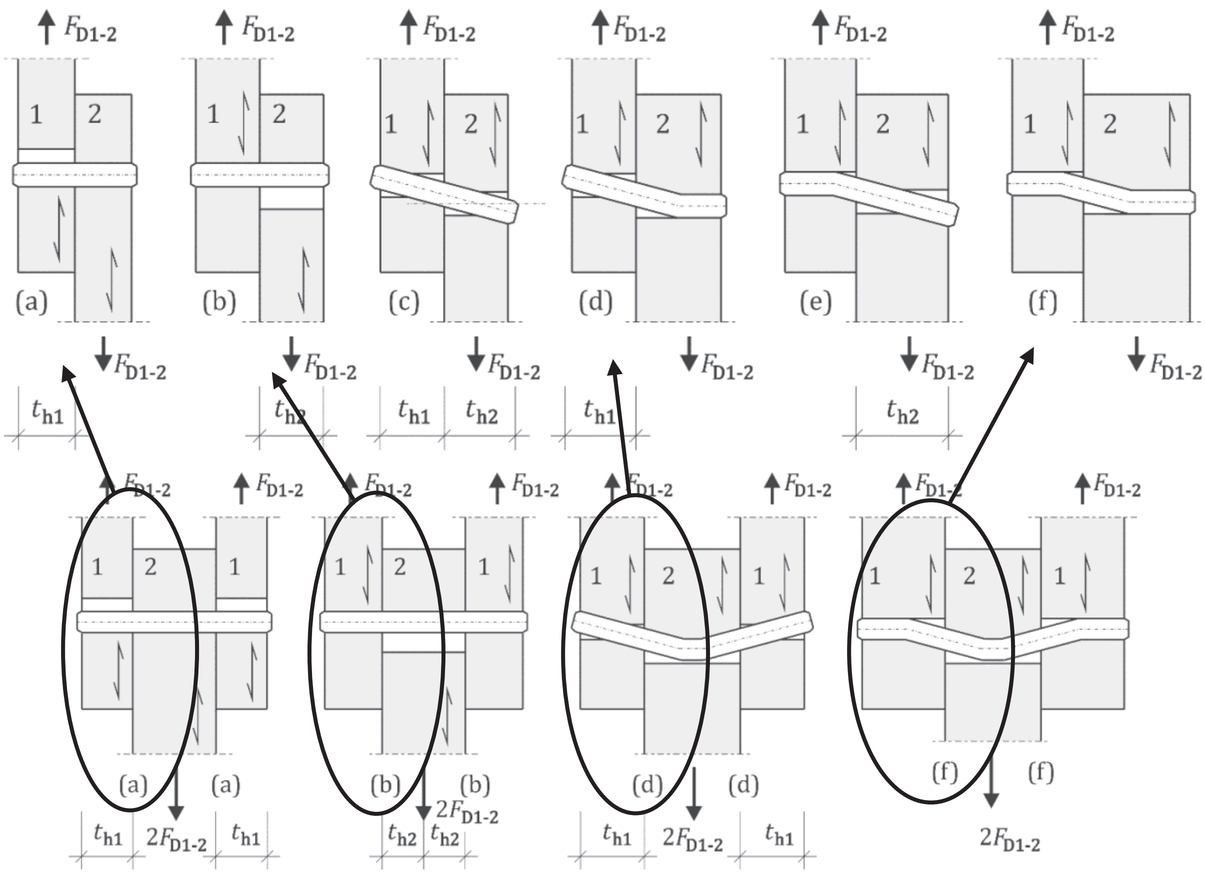

Figure 2 Failure modes according to the EYM for a connection with a laterally loaded fasteners in single shear (top) and double shear (bottom).

2.3.3 Simplification

In addition to the general design formula for the different failure modes as shown in Figure 2, a simplification is given for a quick and simple design of connections. For that purpose the failure mode (f) with two plastic hinges in the fastener per shear plane is taken as the basis for the resistance and a linear reduction for smaller timber member thickness is suggested as done in in the Swiss standard SIA 265:2012 [5] or in the German national annex [6] to the 2004 version of Eurocode 5:

$$F_{D,k} = 1{,}15 \cdot 2\sqrt{\frac{1}{1+\beta}}\sqrt{M_{y,k} f_{h,2,k} d} \cdot \min\begin{cases} t_{h1}/t_{h1,0} \\ t_{h2}/t_{h2,0} \\ 1 \end{cases} \quad (3)$$

The required minimum embedment depth $t_{h1,0}$ and $t_{h2,0}$ in the members 1 and 2, respectively, to obtain failure modes with one or two plastic hinges in the fasteners in single or double shear depends on the embedment strength of the members $f_{h,1,k}$ and $f_{h,2,k}$ (and their ratio β) and the yield moment of the fastener $M_{y,k}$ and its diameter d. With increased strength grade of the fastener, the required thickness to achieve the failure mode with two plastic hinges increases. That means that the effect of a potential overstrength of the fastener should be considered, in order to achieve the desired failure mode as from the design also in the built structure.

Besides connections with metal fasteners also some recommendations for connections with wood dowels are given based on research by [7] & [8]. A simplification is proposed which is based in the Swiss standard for existing structures SIA 269/5:2011 [9].

2.3.4 Connections with multiple shear planes

In connection between more than 3 members, where the fasteners are loaded in more than 2 shear planes, a variety of different combinations of failure modes can occur. The resistance of these connections can be estimated by splitting up the connection into 3 member connections with fasteners in double shear and adding up the resistances of the individual shear planes while assuring compatibility of the failure modes. That means that in shear planes between internal members failure modes with an inclination of the fasteners cannot occur, i.e. the internal members fail either in pure embedment with a straight dowel or a failure where two plastic hinges are present per shear plane. In addition to the compatibility also a balanced distribution of forces between the members should be assured in order to avoid load concentration and brittle failure modes in some members.

Compatibility of the load-displacement behaviour and the balanced share of loads between the different internal and external members of a connection with multiple shear planes is normally ensured if the thickness of the external member is approx. between 35%-50% of the thickness of the internal members. This is based on studies by [10] & [11] and implemented in SIA 265:2012 [5].

2.3.5 Material parameters

In the formulas for the determination of the dowel effect contribution the characteristic embedment strength and the characteristic yield moment are considered as basic material parameters. These values are summarized in clear tables for the different materials and fastener types. New materials or fasteners can be easily added to these tables to allow for future innovation or wider application around the globe.

2.3.6 Rope-effect contribution

In a connection with laterally loaded dowel-type fasteners, the load-carrying capacity of the entire connection in shear consists of the dowel-effect contribution and a part arising from friction between the timber members as well as from the axial load-carrying capacity of the deformed fastener contribute. This latter contribution from the axial force in the deformed fastener to the shear capacity of the connection is referred to as rope effect. In general, the rope effect is 25% of the axial resistance of the fastener. For coated staples and rink shank nails a higher contribution is possible. The rope effect is limited in relation to the dowel-effect contribution for the different fastener types. In the updated chapter the rope effect contribution is more clearly addressed and all the values for the different fastener types are tabulated.

2.4 Spacing, edge and end-distances

The recommended values of minimum spacing, edge and end distances for different fasteners and different materials are clearly arranged in tables. A new feature that was included in the chapter are recommendations for the staggering of fasteners in a connection. This staggering reduces the risk that splitting occurs along the line of the fasteners as long as the fasteners are staggered by one times the diameter size around the axis. In addition, larger staggering enables to achieve a closer arrangement of a larger number of fasteners in a connection. With the design recommendations given in the chapter, it is possible to choose the position of the staggered fasteners along a circular path with respect to the other fasteners. It should be considered that the spacing of the staggered fasteners has to be satisfied between all fasteners in the connection, i.e. that the staggered fasteners are not just added in between the regular fasteners.

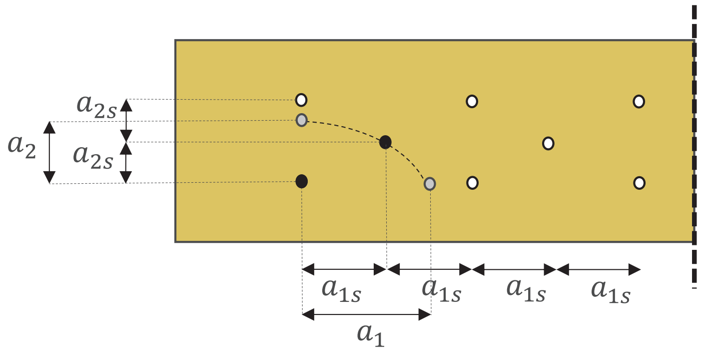

Figure 3 Brittle failure modes.

Not only the recommended and minimum spacing are to be considered for the design but also maximum spacing has to be satisfied in order to ensure the proper performance of a connection. This will ensure that all fasteners in the connection provide and equal contribution to the load-carrying capacity.

2.5 Brittle failure of connections loaded parallel to the grain

The 2004 version of the Eurocode 5 includes provisions for brittle failure of connections in its informative Annex A, where the design model for block shear failure of steel-to-timber connections is described. Splitting was implicitly included in the connection design, by means of the effective number of fasteners. These regulations are a good and important basis for connection design, however, they are not sufficient especially for large and high-performance connections. Some failures of structures in recent years show the clear need for more detailed design specifications against brittle failure modes in connections. The new version of the connections chapters provides this clear design guidance for the different brittle failure modes in the timber surrounding a connection with laterally loaded fasteners, which are:

- Row shear failure
- Block shear failure
- Plug shear failure
- Net tensile failure

The detailed models for the resistances of the different side shear and bottom shear planes as well as head tensile planes have been extensively discussed and validated in different studies [12] - [15]. An additional simplification is proposed, in which the spacing between the fasteners is increased by a factor so that the resistance of the brittle failure modes exceeds sufficiently the failure modes of the fasteners with the development of two plastic hinges per shear plane.

2.6 Brittle failure of connections loaded perp. to the grain

The design approach in the 2004 version of Eurocode 5 was amended by different factors accounting for e.g. dimensions and configuration of the connection, the number of connections in a member as evaluated by [16], and the spacing and distances of connections as evaluated by [17] and included in the 2019 version of SIA 265 [5].

The verification based on shear force in the beam was transferred into a verification of the resistance per connection based on research by [18]. The design approach is valid not only for laterally loaded fasteners but also axially loaded fasteners such as screws or bonded-in rods. The fracture parameter defining the resistance of the connection was updated and is dependent on the density of the timber [19].

2.7 Bonded-in rods

Steel rods glued-into timber have been used as connecting and reinforcing elements in timber structures since almost 50 years. The name “bonded-in rod” was chosen in the chapter in order to distinguish the modern rules for high performance connections with high production quality from old types of glued-in rods with limited performance and production quality.

Careful design, preparation, execution and quality control rules are required to assure the integrity of the bonded-in rod during the desired service life of the structure. The different failure modes of axially bonded-in rods are summarized in Figure 4:

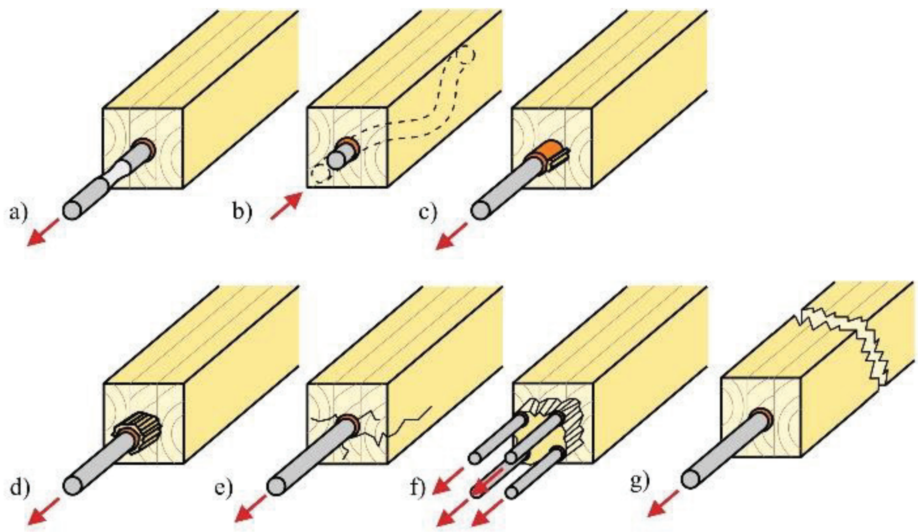

Figure 4 Failure modes of bonded-in rods (from [21] by Pedro Palma): a) tension failure of the rod, b) compression (buckling) failure of the rod, c) failure of the adhesive in the bondline and its bond to rod and timber, d) shear failure of the timber adjacent to the bondline, e) splitting of the timber departing from the bonded-in-rods, f) & g) timber failure of the member in the surrounding of the bonded-in-rod (e.g. net-cross-section, or block-shear failure in a connection with several bonded-in-rods).

The bondline strength is limited by the shear strength of the timber and the shear strength of the adhesive. Only in hardwood the high shear strength of the adhesive is reached, for softwood the bondline strength is limited by timber strength. The actual bondline strength of the adhesive in a certain timber should be determined for a threaded or ribbed rod type according to EN 17334 [20] and needs to be specified for the adhesive products of the different producers.

Especially for connections with multiple simultaneously acting rods, there is a strong need for ductility in the rods to enable the load redistribution and equal loading. In order to ensure a ductile failure mode a sufficient capacity reserve of the brittle failure mode has to be provided. The ductility is difficult to achieve for high steel strength and sufficient capacity reserve of the brittle failure modes (e.g. bondline and splitting failure) should be considered in order to cover possible unintended overstrength of the rod. That is why mild steel rods and small diameters should be preferred together with a recessed bond-line i.e. an unbonded length towards the timber surface.

2.8 Carpentry connections

Carpentry joints have been used for centuries as the most common connecting system in roof trusses. The traditional carpentry connections considered in the chapter are single and double step joints as well as mortise and tenon joints. They all rely on the transfer of compression forces via direct contact. From the long experience with carpentry connections over the centuries, a set of common geometries has established and therefore in the chapter certain geometrical requirements are given. They allow for achieving a proper fit and good load-carrying capacity.

A modern type of carpentry connection is the dove tail connection. This type of connection is a powerful alternative to metal joist hangers. In Eurocode 5 an optimised geometry of the dovetail is specified, which allows the design of the desired load-carrying capacity with regard to the failure modes of splitting in secondary (with a behaviour similar to an end-notched beam) and main beam (with a behaviour similar to a connection loaded perpendicular to the grain).

2.9 Annexes

Besides the common connection types specified in the main body of prEN 1995-1-1:2023 also recommendations for some additional connection types are given in the Annexes.

- Connections with punched metal plate fasteners (PMPF)
- Connections with three-dimensional connectors
- Connections with expanded tube fasteners
- Connections with interlayers

These recommendations address some more industrially used connection types such as the PMPF, but provide also information about novel and more specialised connections such as the expanded tube fasteners offering high ductility. The specifications for connection with interlayers provide extensions for the EYM for other configurations with stiff or flexible interlayers, that can occur in connections with intermediate insulation materials, connections through sheathing on studs, or reinforced connections with densified plywood. The design equations are quite lengthy that is why proper programming in spreadsheets is recommended for the design.

3 Conclusion

The revision and updating of the connections chapter for Eurocode 5 by PT5 and WG5 of CEN TC250/SC5 has resulting in a new chapter considering all the aspects of modern connection in timber structures. By including updated values of material and fastener properties, the chapter provides the basis for an efficient design of modern timber structures. New types of fasteners but also traditional connections not yet considered in Eurocode will provide the full range of connection technology to the engineer. The possibility to update and include new property values for new materials or fasteners in the tables, will facilitate keeping the standard up to date and will enable also the use of the chapter in other parts of the world outside Europe.

4 Acknowledgements

This article is based on the contributions [1] & [22] at WCTE 2021 and IHF 2022, respectively.

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Design of timber bridges

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ABSTRACT: Design rules of Timber Bridges are published as EN 1995-2:2010-12. The second generation implements new knowledge gained the last 20 years. The aim especially was to improve the structure and clarity of the code family. Consolidation on European design practice has been a great part of the work. Though calculating timber bridges has been conducted in a common way, protecting the timber is as much tradition as it is architectural taste. A timber bridge according to the Eurocode is expected to endure for its design service life independent on being located far south or far north in Europe, in the Alpes at high altitude as well as on a windy coast. The term protected timber bridge is introduced, where weathering is not expected to govern the design service life.
All parts of EN 1995-2 have been examined and updated if needed, as presented here.

KEYWORDS: Timber Bridges, Design rules, Eurocode

1. INTRODUCTION

In 2004, the EU and several EFTA states introduced uniform design codes, the so-called EUROCODEs (EC). The goal of the European Committee for Standardization (Comité Européen de Normalisation, CEN) here was to replace the member states' differing or even missing design guidelines by a common set of technical rules that provide the same level of safety and thereby to further minimise barriers within Europe. In 2012, the European Commission issued a mandate for the development of a 2nd generation of the Eurocodes to ensure their long-term applicability and reflect the constant technical developments and knowledge gains (see Figure 1).

Figure 1
European design codes – Eurocodes
SOURCE:
European Commission, 2021

In the work of 2nd generation Eurocodes updates in Eurocode 0 and 1 forced updates for the other EC's. For the series of standards "EN 1995 – Design of timber structures," (EC 5) experts regularly prepare drafts for specific topics in timber construction. To this purpose, six project teams (PT) have been convened since 2015. Today, their work is continued by ten working groups (WG), which before the start of project teams conducted a review of existing content of the EC5, in cooperation and coordination with the national standardisation bodies. After extensive revision of the entire EC 5 series, new versions are available for all members states for current Formal Enquiry (ENQ) which ended 2023, following expected Formal Vote (FV) in April 2025 and publication around 2027 /1/, /2/.

The meaning of the used verb forms are as follows (in all EC's):

shall **requirement**; strictly to be followed ➔ former ()P principle
should **recommendation** (highly); alternative approach where technically justified
may **permission** within the limits of Eurocodes
can **possibility** and capability ➔ only in NOTEs

2. Sustainable Timber Bridge Construction

One of the main topics of editing EN 1995-2 was the implementation of the specifications of EN 1990 and EN 1991-2, in particular requirements for reaching a service life of 100 years. Since construction professionals speak the language of implementation planning, a

new Annex D is suggested with simplified figures exemplifies how timber bridges can be protected given proper service. Service is topic in another new suggested Annex B covering inspection and maintenance of timber bridges. Both annexes are informative and may be subject to changes nationally.
Like the building construction code, the code for timber bridges was extended to include requirements and regulations for the durability of structures, taking into account the issues of corrosion protection, and special structures like transvers post-tensioned timber deck plates or timber-concrete composites. The creep factors for concrete in timber-concrete composite bridges are different from those in known building constructions, as the cross-sections are significantly larger. Accordingly, a new normative Annex A of prEN 1995-2 provides relevant conditional equations. prEN 1995-1-1 shall stipulate requirements for numeric analyses (keyword Finite Element Method, or FEM for short).
Eurocode 8, Part 2 ("Design of structures for earthquake resistance"), will in 2nd generation is also planned to take timber bridges into account. In an Informative Annex C of prEN 1995-2, additional hints for the design of bearings as well as for low or medium seismic areas are given. It is also relevant to point to the Informative Annex E, which contains suggestions to be considered in view of deformations and dimensional changes of timber constructions under changing environmental conditions such as temperature or timber moisture, and notes on transversely prestressed timber deck plates (among other things for the "cupping" of the deck sides) /2a/.
Most regulations on deck plates (timber decks) were now added to the normative Annex of prEN 1995-1-1, as these regulations can also be applied to, e.g., nail-laminated timber constructions. It was also decided to move fatigue requirements into the general part 1-1 as these may be necessary also for buildings with cyclic loads such as industrial buildings, crane structures, highway traffic sign posts, wind turbine tower, or bell towers. With the technical work basically being done, the document is being translated into German and French before being sent on public Enquiry for 16 weeks started September 2023. The remaining steps of the standardisation process are shown in /1/ and /2/.

2.1. Durability of wooden members

General requirements regarding expected service life, i.e. design service life T_{lf}, that form the basis for all bridge design in Eurocodes are given in EN 1990, A.2. Together with recommendations on Quality management the requirements on Durability as well as on Inspection and Maintenance form the basis of a bridge building. These are defined as:

Definition ***Maintenance***

set of activities performed during the service life of the structure so that it fulfils the requirements for reliability

Chapter ***Durability***

All structural parts that rely on a design assumption of inspection and maintenance in order to satisfy their durability requirements over the design service life ***shall*** *be designed to permit inspection and maintenance.*

Subclause ***Quality management***

Appropriate quality-management measures ***should*** *be implemented to provide a structure corresponds to the design requirements and assumptions.*
The following quality-management measures ***should*** *be implemented:*
- organizational procedures in design, execution, use and maintenance
- controls at the stages of design, detailing, execution, use and maintenance.

Based on this, different categories are defined for design service life. For bridges 100 years is the basic option or choice - independent of material types. Lower service life may be relevant for simple bridges used for instance in recreational purposes where consequence of failure is very little, but still 50 years are expected. Further lower service life is given for replaceable structures (25 years) and temporary or unprotected structures (10 years).

For timber bridges achieving a design service life of 50 years the design requirements are the same as for building structures (see general part of EC 5) – but their foundations as well as steel tension components shall be designed for 100 years. Requirements for 100 years service life are outlined in the bridge part, comprising:

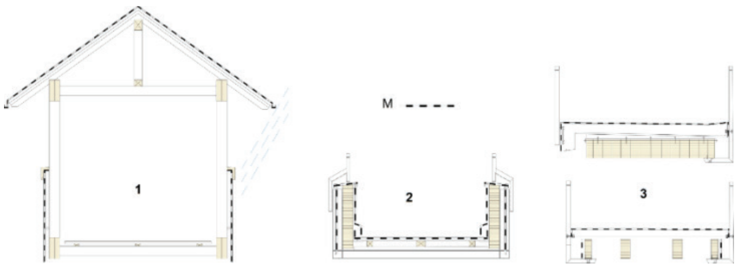
- Requirements on design;
- Recommendations on structural protection;
- Requirements membranes;
- Requirements on steel protection embedded in timber structures.

Environmental actions, e.g. expected moisture variations and thermal actions, are included in simplified calculation models depending on member size. General information on moisture variations are given in the main part.
For the design of durable timber bridges the term protected and unprotected member are included. The definitions are:

Protected Member

structural member not exposed to direct weathering such as rain, snow, or other sources of moisture ingress

Examples of protected timber bridges are given e.g. in Figure 2.



Key
M Membrane or weather-resistant layer
1 Covered footbridge (bridge with a roof)
2 Trough bridge
3 Deck bridge

Figure 2: *Examples of protected timber bridges*

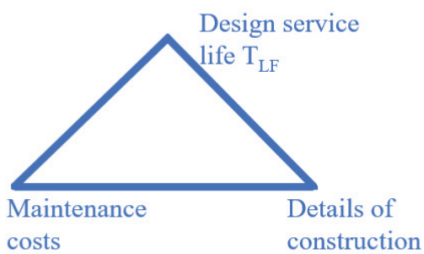
Unprotected Member

structural member that is not protected or partially unprotected from weathering but is within the limits of Service Class (SC) 3

The methodology is that a protected timber bridge is expected to last for 100 years. When parts of a structures are not within the definition of a protected member these must either be easily replaceable or the expected service life will be less than 100 years.

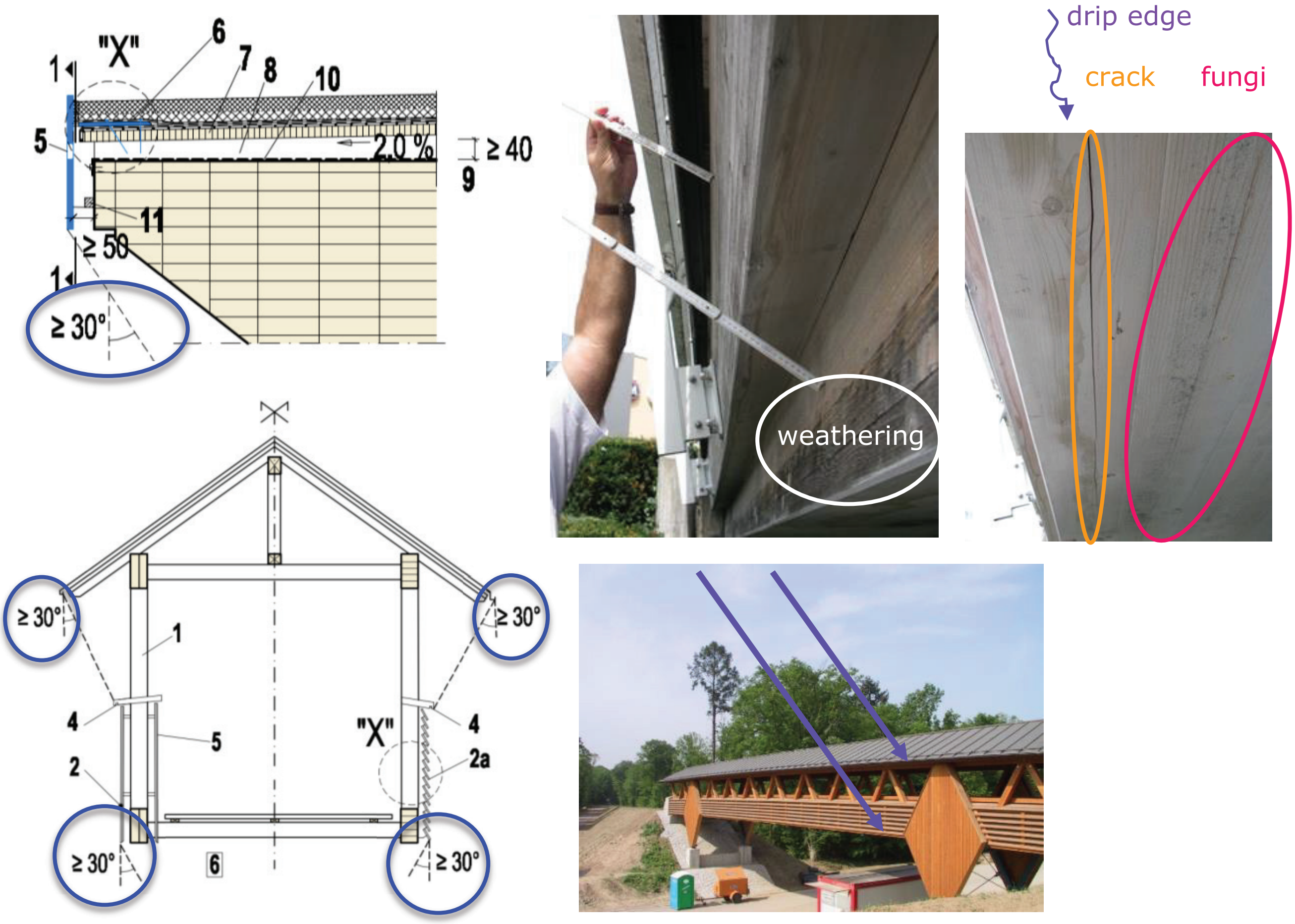
Durability and thus sustainability ensure the economic viability of timber structures. Therefore, the following so-called "magic triangle" must be observed:

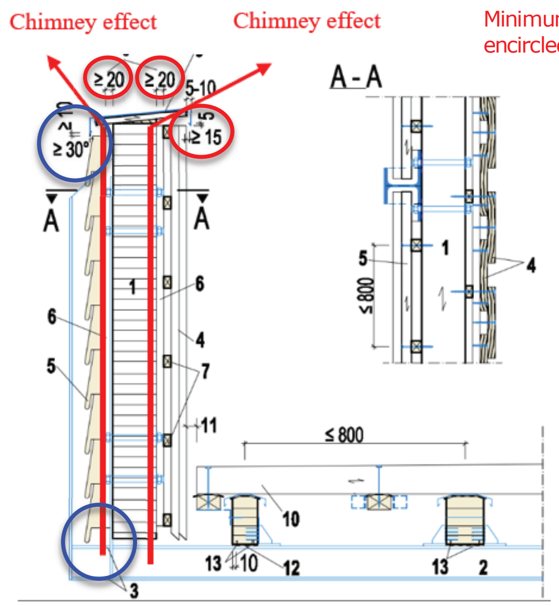
Requirements on basic structural protection are given in EN 1995-1-1 and EN 1995-2, in some countries with additional nation requirements. This leads to a higher robustness of the expected service life, expecting to lower maintenance costs.



2nd generation of EN 1995-2 includes detailing by figures in Annex D how timber bridges can generally be protected. Five possibilities for basic structural timber protections are given (see Figure 3), together with more detailed examples on expansion joints between superstructure and road (three possible solutions) and bridge caps (2 examples).
Furthermore, a suggested monitoring scheme is included as monitoring timber bridges may be a useful addition to inspection, in some European countries mandatory. Currently

an arch bridge is taken as example showing which part of the bridge is expected to be critical and thus wise instrumenting, also with regard to the Use Class (UC) according to EN 355.
Because of translation of European standards all figures are language neutral, creating rather lengthy keys to each figure (see Figure below).





Minimum ventilation openings for the chimney effect encircled in red

*) Shuttering elements partially easy to dismantle for inspection.

Key

A-A	*Section A-A*
1	*Main girder*
2	*Steel frame*
3	*Borehole in top and bottom flange*
4	*Cladding (generally outside) *)*
5	*Vertical weather boarding (outside) *)*
6	*Vertical battens*
7	*Horizontal battens*
8	*Ventilation openings, horizontal ≤ 100 cm³ / m, vertical ≤ 50 cm² / m*
9	*Aluminium plate or equivalent*
10	*Grooved planks (e.g.)*
11	*Gap with 15°mm if floor cover shuttering, 30°mm if cover stripe, groove and tongue*
12	*Rubber or elastomer mat*
13	*Weather groove (notch)*

Figure 3: Constructional wood protection - possibilities:
above: Asphalt surface

The angle of at least 30° to the vertical at which windblown rain is assumed to fall is shown in blue

middle: Roof and claddings
below: Sheating of through bridge

2.2 Durability of steel members

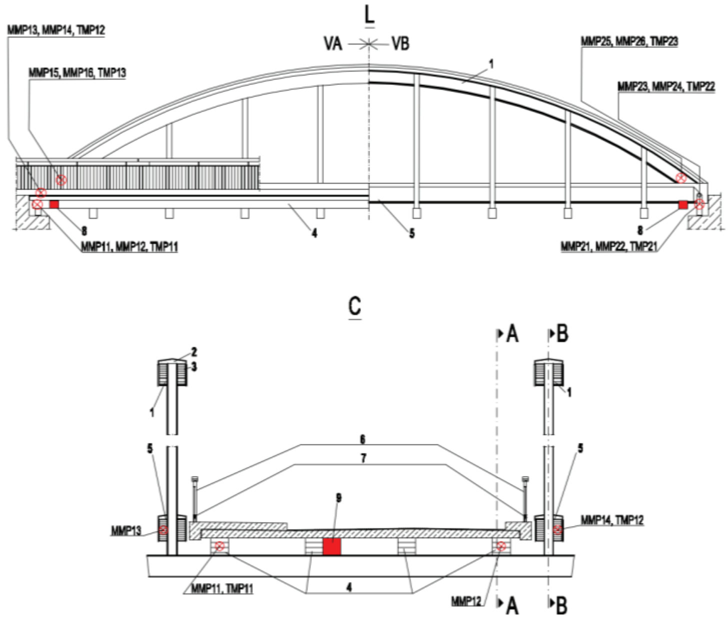
For steel members the updated standard gives requirements of protection of steel members in wooden structures by declaring a timber exposure category T_E. Different protection levels depending on an atmospheric exposure category C_E, the service class SC and the design service life of 100 years [in brackets 50 years] results in different recommendations of minimum protection either by steel grade or zinc coverage (see Table 1). Requirements of protection of steel in general is covered by Eurocode 3.

Table 1: Timber exposure T_E-categories and atmospheric exposure C_E-categories with examples of minimum requirement for thicknesses for pure zinc coating, hot-dipped galvanized coating, and types of stainless steels for timber bridges (outdoor) with a design service life of 100 years [50 years]

Situation	***Timber exposure category*** [a] **T_E**	***Atmospheric exposure category*** [b] **C_E**	***Typical atmospheric exposure*** [c] *(informative)*	***Examples of minimum***	
				zinc thickness [d]	***stainless steel grade (type)*** [e]
Protected outdoor with access of pollution (SC2 and SC3)	*T_E3/T_E4*	*C_E2*	*L_{sea} > 10 km L_{street} > 100 m and/or low polluted area (< 5 µg/m³ of SO_2)*	*T_R3: 40 µm* [f] *(n/a* [g] *if T_E4) [20 µm* [f] *(55 µm if T_E4)]* [h]	*CRC II (e.g. 1.4301)*
	T_E3/T_E4	*C_E3*	*10 km > L_{sea} > 3 km 100 m > L_{street} > 10 m and/or medium polluted area (5 µg/m³ ≤ SO_2 ≤ 30 µm/m³)*	*C_R3: 110 µm [80 µm]* [h]	*CRC III (e.g. 1.4401)*
	T_E3/T_E4	*C_E4*	*3 km > L_{sea} > 0,25 km L_{street} < 10 m and/or high polluted area (30 µg/m³ < SO_2 ≤ 90 µm/m³)*	*C_R4* [b]*: n/a* [g] *[110 µm]* [h]	*CRC III (e.g. 1.4401)*
	T_E3/T_E4	*C_E5*	*L_{sea} < 0,25 km and/or very high polluted area (90 µg/m³ < SO_2)*	*C_R5* [b]*: n/a* [g]	*CRC III (e.g. 1.4529)*
Permanent in contact with ground- or fresh-water (SC4)	*T_E5*	*n/a* [g]	*For T_E5/SC4 especially in case of seawater each case should evaluated individually.*	*C_R5* [b]*: n/a* [g]	*CRC III to CRC V*

2.3 Inspection and maintenance

See introduction clause 2. and subclause 2.1 (→ Annex B)
Regarding sealant systems as well see presentation from Mr. Prof. Dipl.-Ing. Andreas Müller /3/.
As already mentioned a monitoring of timber bridges may be a useful in addition to inspection. Currently an arch bridge is taken as example (see Figure 4) showing which part of the bridge is expected to be critical and thus wise instrumenting, also with regard to the Use Class (UC) according to EN 355 (Table 2).



Key

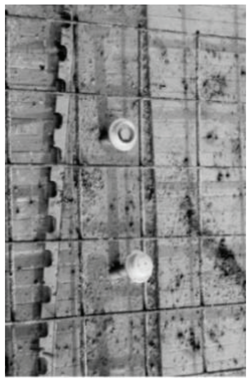
L	*Longitudinal section*
VA	*view A-A*
VB	*view B-B*
W	*Wood protection*
1	*Arch truss UC ½*
2	*Roof board*
3	*Lead sheet*
4	*Longitudinal beam*
5	*Pliers beam*
6	*Railing vertical components UC 3.1*
7	*Railing horizontal component UC 3.2*
8	*Instrument box 1 (or 2)*

Figure 4: Detailing T-Mon – Moisture Monitoring – Example arch truss (timber bridge) – Use classes UC

Table 2: Components of an arch road bridge (example)

Component	***Use class (UC) [Service class SC)]***	***Protective measure***	***Wood type***	***Durability Class (DC)***
	EN 335 [prEN 1995-1-1]	***EN 1995-2 Sample drawings***	***EN 13556***	***EN 350, Table B.1***
Longitudinal beam	*2 [2]*	*Weather protection through roadway slab and transition 1, protection of the truncated wood fibres, protection against insect attack through technical drying, visibility and control of insect infestation*	*Spruce as glulam*	*4*
Arch truss / pliers beam	*2 [2]*	*Weather protection by cladding and shuttering, protection against insects by technical drying and insect protection grid, visual inspection every 6 years by removal of claddings*	*Spruce as glulam*	*4*
Railing	*Vertical: 3.1 [3] Horizontal: 3.2 [3]*	*None, maintenance component*	*European larch*	*3*

2.4 Timber-concrete Composites (TCC) and Integral abutments



TCC decks are included in the updated bridge standard, giving requirements on design and recommendations on durability and design. In the Technical Specification TS CEN TS 19103 the load-bearing capacity and deformation behavior of a notched connection in a girder as a shear connection is regulated. Looking on the uplift forces of the notch the loading for the waver-head screw (see the figures on the right hand side) are given.

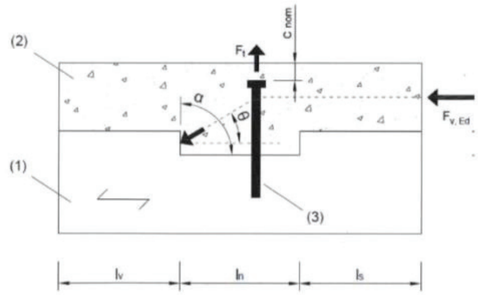


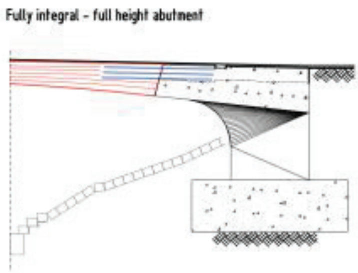
Figure 10.2 – Notched connection dimensions

Based on the research mainly made at the University of Stuttgart the rheological material behavior (shrinkage and swelling) is temporary conversely. Therefor the period from 3 to 7 years has to be taken into account.

Creep must be evaluated carefully and as such this is also topic in the updated draft. For a more detailed information on the topic see /5/ - presentation from Mr. Prof. Dr.-Ing. Jörg Schänzlin.

Basically all connectors regulated by a national technical approval or European Technical Assessment (ETA) may be used.

Integral timber bridges, bridges with a flexural connection to a concrete abutment (see Figures on the right hand side and the picture Figure 5 below showing the Rokoko- and the Bahnhofsbrücke in Schwäbisch Gmünd, Germany) have gained some experience and are also included in the timber bridge code.



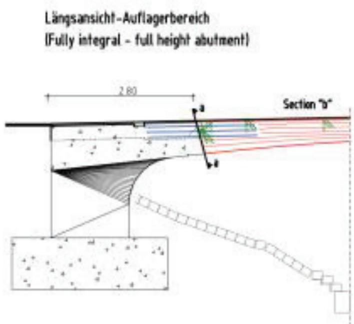


Figure 5: Examples of integral timber bridge designs

2.5 Timber Deck Plates

Timber deck plates comprise decks made of solid-wood beams arranged side by side in the direction of span, clamped together (see Figure 6). As a result, the (punctual) wheel loads can be distributed over several beams (see Figure 7 above). Nowadays, these deck plates (timber decks) are largely used in Scandinavian and Baltic states often using glued laminated timber (GL) as beams and stressed together with steel rods. Requirements regarding these structures have been updated representing state of the art including newer research on the topics. This also includes requirements on modelling of the bridge decks using Finite Element Software as well as updated recommendations on friction coefficients (see Table 3) and requirements to minimum stress forces.

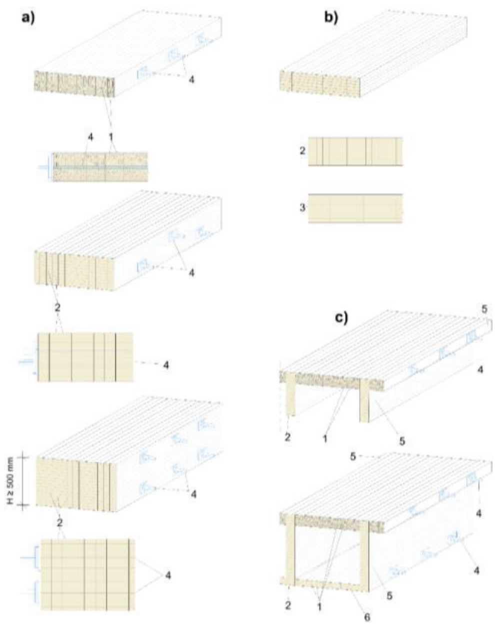


Figure 6: Examples of transvers post-tensioned timber decks for bridges made of lamellas

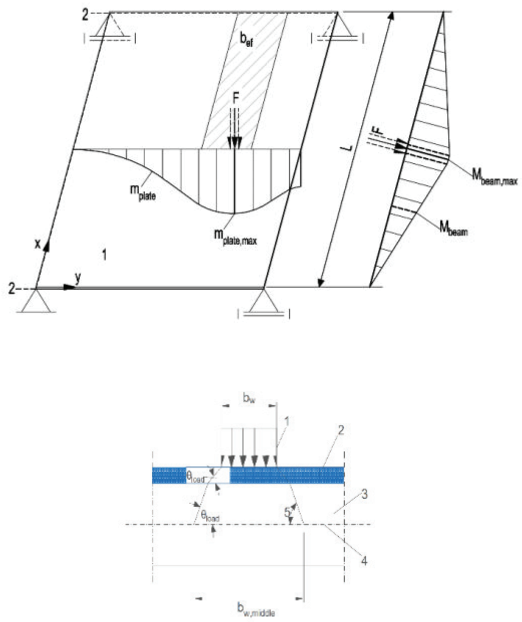


Figure 7: Distribution of concentrated load .

Table 3: Values of Coefficient of Friction μ for softwood

Lamination surface roughness	Perpendicular to grain μ_{90} [-]	Parallel to grain μ_0 [-]
Sawn timber to sawn timber	0,40	0,30
Planed timber to planed timber	0,30	0,25
Sawn timber to planed timber	0,40	0,30
Timber to concrete	0,40	0,40

2.6 prEN 1998-2: seismic design / earthquake resistance

In the new "Eurocode 8: Design of structures for earthquake resistance — Part 2: Bridges" timber bridges will be considered now. The proposals given by PT6 from the timber side were mostly assumed – mainly in the informative Annex C. prEN 1995-2, Annex C (informative as well) provides supplementary information to EN 1998-2, Annex C in bearing and timber bridges in low and medium seismic areas.

Further reading on updates may be found in /2/ and /2b/.

3. Service limit state

3.1 Deflections and deformations

Requirements on deflections due to traffic-load and wind-force have been updated (see Table 4) due to the requirements in EC 0. These actions should be verified and limited in order to prevent unwanted dynamic impact due to traffic, infringe of required clearances and cracking of surfacing layer, ensuring also sufficient run-off from standing water.

Table 4: Limiting values for deflections of timber beams, plates and trusses (NDP)

Action (Frequent load value)	Range of limiting values	
	vertical	**horizontal**
Traffic loads on road bridges	L/500 to L/650	-
Low traffic loads on footways, cycle tracks and pedestrian bridges	L/500 to L/900	-
Wind forces	-	L/600 to L/1500

3.2 Vibrations/Oscillations and damping

A rather large update has been conducted on the subjects vibrations and damping. Simplification regarding requirements given in other parts of Eurocodes are introduced in the timber bridge part. An example is shown in Figure 8, where different requirements are gathered in one requirement, see black line in Figure 8.

For further reading see /4/ - presentation given by Mrs. Prof. Dr.-Ing. Patricia Hamm.

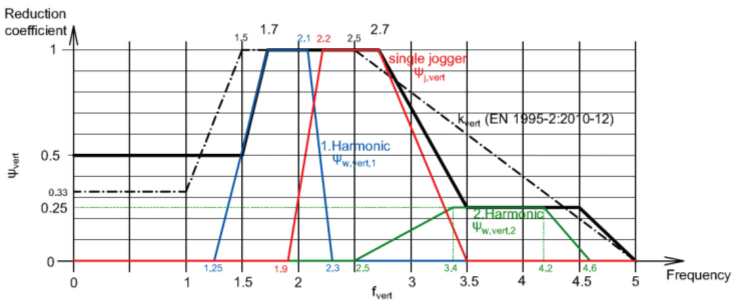


Figure 8: Relationship between the vertical eigenfrequency f_{vert} and the coefficient ψ_{vert}

4. Fatigue

As already mentioned it was decided to move fatigue requirements into the general part EN 1995-1-1. This means that in EN 1995-2, only those parts were kept that are relevant for timber bridges, in particular:

- some general parts concerning the fatigue assessment of timber structures;
- parts of the document that deal with fatigue load models;
- a simplified fatigue verification model especially for bridges.

Basis in fatigue verification is the stress ratio R_T as the arithmetical minimum stress to the maximum stress of a particular stress cycle in timber design Since the factor representing the reduction of fatigue strength with number of load cycles k_{fat} values depend on R_T, a simplification is also required to offer a real advantage over the 'full' k_{fat} verification (see Table 5). Therefore, it is proposed to consider only whether the fatigue loading is alternating or not and to use the k_{fat} values for $R_T = 0$ or $R_T = -1$, respectively.
The k_{fat} values were evaluated for two lanes and 2 x 10^6 cycles (trucks), giving anticipated

100 years design service life using an ß-factor equal to 3 (substantial consequences). This yields a design load cycle number of 1.2 x 10^9.

Table 5: Reduction factors k_{fat} for simplified verification for ß = 1 [ß = 3]

	Compression	***Bending and tension axial***	***Connections with dowels***
$-1 \leq R < 0$ *(reversed loading)*	-	*0,13 [0,08]*	*0,04 [-]*
$0 \leq R$ *(non-reversed loading)*	*0,52 [0,49]*	*0,17 [0,13]*	*0,28 [0,24]*

5. Perspective

The completion of the work on the European timber construction standards is scheduled for 2026/2027. Current status for the timber bridge code is that the comments given in the public Enquiry 2023 (together will all other parts on timber structures; i.e. part 1-1 General rules and rules for buildings, part 1-2 Fire design and part -3 Execution) are answered. After this ENQ no new technical content will be added; only changes to what is suggested will be made, thus most of the essential changes are already known.

The scope of the standard will inevitably grow, as new timber construction products need to be considered and known design approaches need to be extended and optimised. The update is guided by the central interest of increasing the user-friendliness – not only by profiting from digital availability and efficient search options but also by restructuring, homogenising, and simplifying the regulations.

Nevertheless, as with the adjustment of the first generation of Eurocode 5, an additional process of learning, training, and education will be necessary, with this process starting already prior to the final publication. In conclusion, it may be stated: the second generation of Eurocode 5 is not a revolution but an evolution that consistently builds on the experiences and principles of the previous version.

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TCC and Integral Bridges.
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Eurocode 5 – 2nd Generation – Fire Design

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Summary

The revision work of the new EN 1995-1-2 was performed by a Project Team (PT), which consists of Andrea Frangi (chair, ETH), Alar Just (TalTech), Norman Werther (TU Munich), Jouni Hakkarainen (Eurofins), Joachim Schmid (ETH), and additional members from 2021 – Harald Krenn (KLH), Renaud Blondeau (Stora Enso) and Gordian Stapf (Henkel).

Basis for the drafting work are extensive documents, reports and publications with the update state-of-the-art with regard to the structural fire behaviour and fire design of timber structures, e.g. the European Technical Guideline “Fire safety in timber buildings” or the reports prepared in the frame of the recently concluded COST Action FP1404. The PT started his work on June 2018 and regularly reports to the Working Group WG4 of CEN/TC250/SC5, which is responsible for the revision of EN 1995-1-2. During the last 3 years, the PT prepared three drafts, which were reviewed by the WG4 and commented by the national standardisation bodies. The first draft (May 2019, 75 pages) received 265 comments, the second draft (Mai 2020, 134 pages) 624 comments and the third draft (November 2020, 138 pages) 364 comments. The final draft of EN 1995-1-2 was submitted at the end of August 2021 and received 396 comments. Formal Enquiry of the document was held from September 2023 to January 2024 and received 856 comments.

The following list gives some highlights of the new EN 1995-1-2.

Key words: Eurocode 5; Fire resistance; European Charring Model; Separating Function Method

1. Structure of the new EN 1995-1-2

Structure of the new EN 1995-1-2 follows the harmonised logic of all fire parts of the Eurocodes. The structure and also the first four chapters for all fire parts of the Eurocodes are written by TC250 "Horizontal Group Fire". This has resulted in harmonized structure, which contributes to user-friendliness. Table 1 provides an overview of the structure of the draft standard and a comparison with the currently valid EN 1995-1-2:2004. The principle of a three-stage possibility of verification levels with different levels of complexity and accuracy, which is already known from other Eurocodes, is now also fully established for timber construction. Thus, in the future there are

- tabulated design data (Chapter 6),
- simplified design methods (Chapter 7) and
- advanced design methods (Chapter 8)

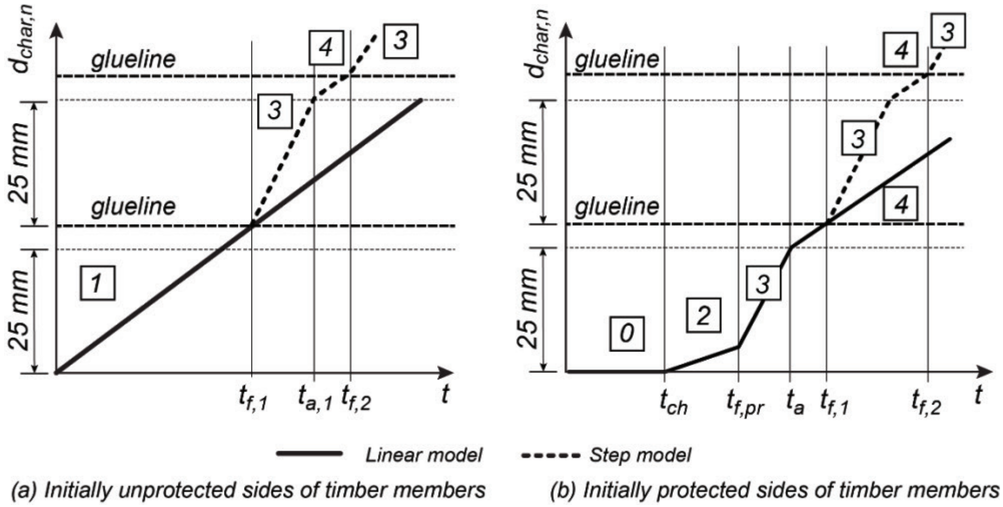
In addition to the principles for simplified design models already known in the current EN 1995-1-2 and the basics for numerical simulation models, Chapter 6 in the new EN 1995-1-2 lists for the first time proven construction structures or predefined characteristic values (such as the protective effect (t_{prot}) of panels or for the zero strength layer dependent on the lay-up of the cross-section for cross-laminated timber). In this way the user is given a very simple and efficient way of verifying fire resistance. Despite the increased scope of regulations and the expansion of the scope of application, the structure adapted in this way will enable simple application.

Table 1 Comparison of the content and structure between the current EN 1995-1-2 and the revision

EN 1995-1-2:2004		EN 1995-1-2:2025 Draft	
1	General	1	Scope
	-	2	Normative references
	-	3	Terms, definitions and symbols
2	Basis of design	4	Basis of design
3	Material properties	5	Material properties
4	Design procedures for mechanical resistance	6	Tabulated design data
5	Design procedures for wall and floor assemblies	7	Simplified design methods
	-	8	Advanced design methods
6	Connections	9	Connections
7	Detailing	10	Detailing
Annex A: Parametric fire exposure		Annex A: Design of timber structures exposed to physically based design fires	
Annex B: Advanced calculation methods		Annex B: Assessment of the bond line integrity in fire	
Annex C: Load-bearing floor joists and wall studs in assemblies whose cavities are completely filled with insulation		Annex C: Determination of the basic charring rate	
Annex D: Charring of members in wall and floor assemblies with void cavities		Annex D: Assessment of Protection Level (PL) of the cavity insulation	
Annex E: Analysis of the separating function of wall and floor assemblies		Annex E: Assessment of external flaming	
Annex F: Guidance for users of this Eurocode Part		Annex F: Assessment of the failure time of fire protection systems	
-		Annex G: Implementation rules for the Separating Function Method	
-		Annex I: Design model for timber frame assemblies with I-shaped linear timber members	
-		Annex M: Material and product properties for the design with EN 1995-1-2	
-		Annex T: Determination of temperature in timber members	

2. European Charring Model

Charring has extensively been dealt and the current model (in the future renamed as the European Charring Model) has been generalised considering the different phases of protection and the different modification factors for charring in a more systematic way. Further, the charring model clearly distinguishes two cases (bond line integrity maintained or not maintained during the fire exposure). See Figure 1. Supplementary guidance for the assessment of the bond line integrity in fire has been included in the new Annex B.



Key:

0	Encapsulated phase (Phase 0)
1	Normal charring phase (Phase 1)
2	Protected charring phase (Phase 2)
3	Post-protected charring phase (Phase 3)
4	Consolidated charring phase (Phase 4)

$d_{char,n}$ - notional charring depth
t - time
t_{ch} - start time of charring
$t_{f,pr}$ - failure time of the fire protection system
t_a - consolidation time

Figure 1: Phases for timber members according to the European charring model.

2.1. Bond line integrity

To evaluate the performance characteristic of the bonding in case of fire, two test methods are introduced in Annex B. Consequently examination is possible of the surface bonding of timber layers and the finger-jointing in the flanges of web beams.

For face bonds, the charring rate of a tested CLT or glulam specimen is compared to a solid wood reference in 120 minutes standard fire test in a horizontal position. The bond line integrity is assessed as maintained if the difference in charring rate of test specimen do not exceed 5% of the charring rate of solid wood reference.

For the assessment of finger-joints in the flanges of I-joists in case of fire, a test method was introduced in Annex B with small test specimens that are exposed to constant high temperature. The test method was developed as part of the FIRENWOOD research project and calibrated with fire tests. Based on the test results, the finger joints are divided into three performance classes, which are taken into account in the design for the fire case.

2.2. Time limits of charring phases

Time limits between phases for initially protected timber members are defined by start time of charring t_{ch}, failure time (or fall-off time) of the fire protection system $t_{f,pr}$ and consolidation time t_a. For structures with bond line integrity not maintained, the fall-off time of charred layers $t_{f,i}$ is considered.

Start time of charring t_{ch} will be designed according to Separating Function Method.

Fall-off time $t_{f,pr}$ is one of the most important parameters influencing the fire resistance of initially protected timber structures, especially concerning timber members with small cross-section. In the new Eurocode the failure times (defined as fall-off times) of different panels, including gypsum plasterboard Type A and F and gypsum fibreboards are given with simplified equations based on a large data base of fire tests. Further, for the fire design it is possible to use failure times based on full-scale fire tests performed according to EN 13381-7.

The temperature increase behind gypsum plasterboards backed by insulation occurs faster and the fall-off of the board occurs earlier. Hence, the fall-off from a timber surface like CLT may be delayed due to decreased heat transfer and distance between fasteners. Fall-off time of the boards covering the void cavities is also delayed if compared with insulated cavities of timber frame assemblies.

The protective properties of clay and lime plaster have been investigated experimentally and numerically. The fall-off of time of clay plaster depends on the fixation as well as the adhesion between clay and the fastening system. Fixation of clay plaster onto CLT can be excellent and, therefore, clay plaster offers good protection to the timber structure.

2.3. Basic and notional design charring rate

Notional design charring rates in different phases and for different types of members will be calculated using applicable modification factors.

$$\beta_n = \prod k_i \cdot \beta_0 \quad (1)$$

β_n is the notional design charring rate within one charring phase, in mm/min;

β_0 is the basic design charring rate, in mm/min;

$\prod k_i$ is the product of applicable modification factors for charring.

In the EN 1995-1-2:2025 the basic design charring rates β_0 are given for European softwood (Table B.2 in EN 14081-1), some hardwood species (beech, oak, ash) and also panels made of LVL, OSB, fibre boards, particle boards and plywood. Compared to EN 1995-1-2:2004 the basic design charring rates of some wood based board products are decreased.

the basic design charring rates for engineered wood (glulam, CLT) should be chosen according to the wood species that lamellae are made of.

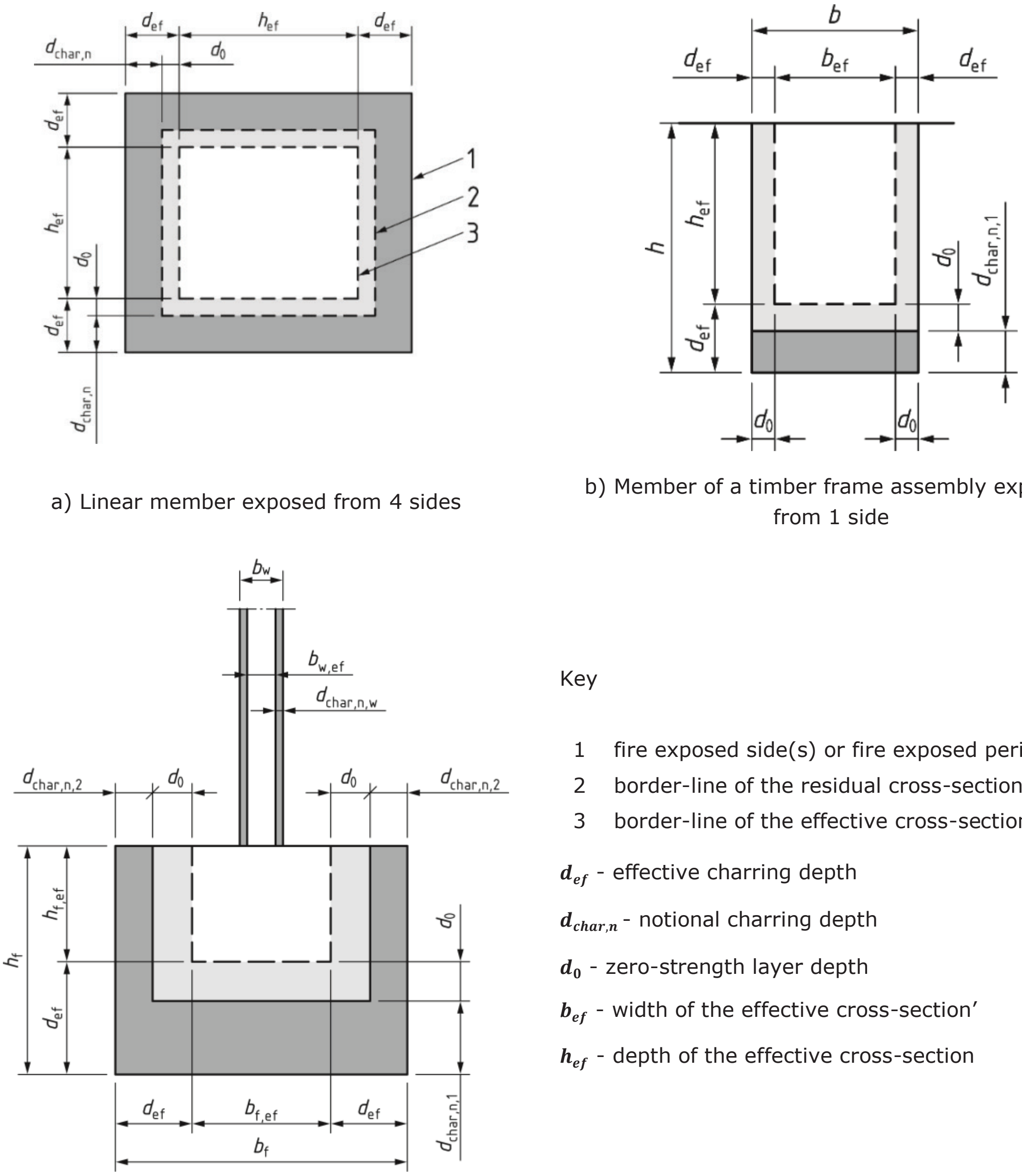
The basic design charring rates for species and wood-based boards not listed in the EN 1995-1-2 should be determined using the assessment method at Annex C.

3. Effective Cross-Section Method

As simplified design method only the current Reduced Cross-section Method (in the future renamed as Effective Cross-section Method) is given. The current Reduced Properties Method has been deleted. The Effective Cross-section Method has extensively been revised and its use extended to all common structural timber members, including cross-laminated timber panel (CLT), timber frame assemblies and timber-concrete-composite elements (TCC).

According to the effective cross-section method the initial cross-section of a timber member is decreased by a notional charring depth and by zero-strength layer depth from the respective sides. Strength properties of the effective cross-section will not be decreased for the fire situation. The heating effect is taken into account by a zero-strength layer depth.

Many fire test results from the last decades show that zero strength layer depth 7 mm given in the current Eurocode 5 leads often to unconservative results in the design. In the 2nd generation of Eurocode 5 the zero-strength layer depths are increased to 10 mm for bending and tension members and 14 mm for compression members.



a) Linear member exposed from 4 sides

b) Member of a timber frame assembly exposed from 1 side

c) I-shaped member of timber frame assembly

Key

1 fire exposed side(s) or fire exposed perimeter
2 border-line of the residual cross-section
3 border-line of the effective cross-section

$\boldsymbol{d_{ef}}$ - effective charring depth

$\boldsymbol{d_{char,n}}$ - notional charring depth

$\boldsymbol{d_0}$ - zero-strength layer depth

$\boldsymbol{b_{ef}}$ - width of the effective cross-section'

$\boldsymbol{h_{ef}}$ - depth of the effective cross-section

Figure 2: Examples of the effective cross-sections.

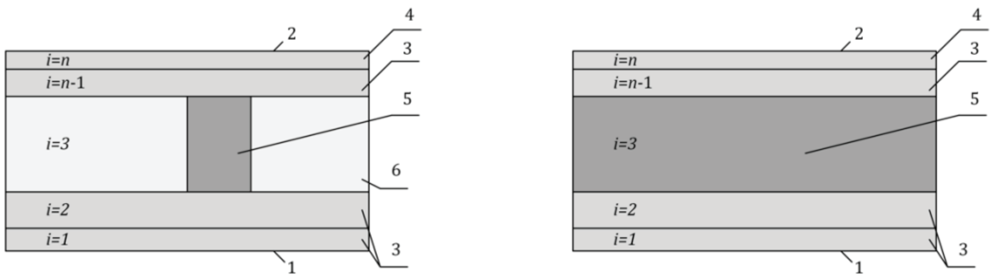
The current annexes C (timber frame assemblies with filled cavities) and D (timber frame assemblies with void cavities) has extensively been improved and moved to the main part of EN 1995-1-2. The revised content is normative. The design model for timber frame assemblies with filled cavities is based on the Effective Cross-section Method and allows considering the performance of different types of insulation (mineral wool, cellulose, wood fibre, etc.). The performance of the insulation can be evaluated with small-scale fire tests and assessed in 3 different protection level according to the new Annex D.

Calculation of the effective cross-section is given for cross-laminated timber, taking into account the load-bearing and non-load bearing layers.

4. Separating Function Method

The current Annex E (Component additive method) for the verification of the separating function has extensively been improved and moved to the main part of the EN 1995-1-2. The revised content is normative and the design method for separating function has been extended to 120 minutes fire resistance.

Heat path through the timber members or other materials as panels and insulations maybe calculated by taking the contribution of each layer into account starting from the fire exposed side. Layers can be combined and changed easily. Total insulation time of an assembly is the sum of contributions of all layers. Generic values for protection times are given for wood-based products, gypsum boards, clay and lime plasters, mineral wool and cellulose based insulation materials and as well as cement based screed. The method is open to include new materials or products using the procedure in the new Annex G.



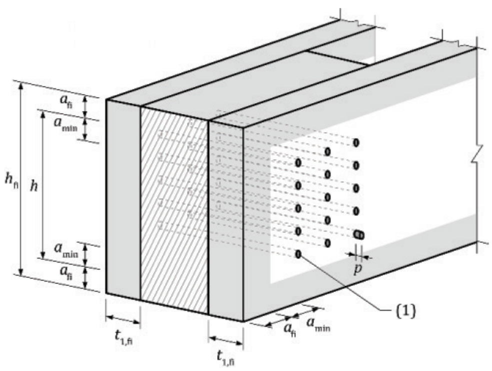
Key:

1	Fire exposed side
2	Unexposed side
3	Panels as protective layers
4	Panel as insulating layer (last layer n)
5	Timber member as protective layer
6	Cavity (insulation or void) as protective layer

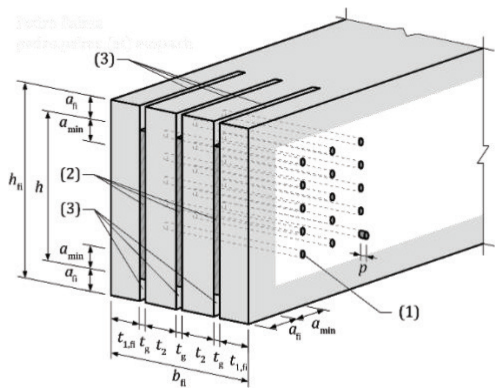
Figure 3: Definition of layers for the Separating Function Method.

5. Connections

Calculation method for connections is extended and enhanced. Improved rules for the fire design of connections up to 120 minutes fire resistance are given based on extensive experimental and numerical analysis. Further, tabulated design data have been included allowing a simple fire design of connections.



a) Timber-to-timber connection



b) Steel-to-timber connection

Figure 4: Examples of connections.

6. Detailing

Detailing rules shall be satisfied when simplified design methods or tabulated design parameters are used.

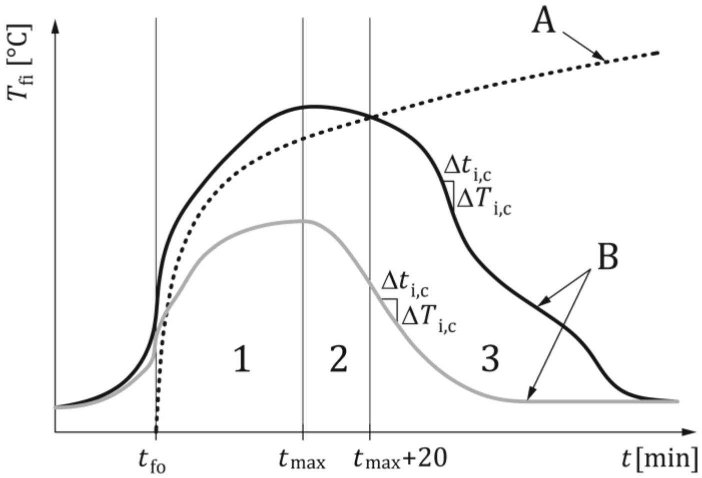
The rules for detailing were extended and enhanced compared to current version of EN 1995-1-2. In addition to rules for panels and insulation (dimensions, spacings, fixation, etc), rules for joints in and between elements and to other adjacent components as well as rules for penetrations and openings are given.

7. Design for physically based fires

For the design of timber structures exposed to physically based design fires improved rules and design methods have been developed and given in the new Annex A.

Design methods for any temperature-time curve including the parametric fires are given. According to the new Eurocode timber structures can be designed until burnout including the contribution of structural fire load to the total fire load. The calculation of structural fire load is performed according to Annex H of a new EN 1991-1-2.

The standardized methods for physical based fires create new possibilities for design of fire resistance of large and tall timber buildings for a full fire scenario according to Eurocode 5.



Key

t_{fo}	time of flashover	2	intermediate phase
t_{max}	time of maximum compartment temperature	3	cooling phase
$\Delta t_{i,c}$	time difference in the cooling phase (evaluation step i)	A	standard fire
$\Delta T_{i,c}$	temperature difference in the cooling phase (evaluation step i)	B	physically based fire
1	heating phase		

Figure 5: Compartment fire temperature: definition of phases for physically based fires.

8. Summary

It is expected that the second generation of EN 1995-1-2 will fill most gaps of the current EN 1995-1-2 and will allow a safe and economic design of timber structures in fire.

The scope of the standard has been growing due to the necessary consideration of new products made of wood, the demand for more accurate design and the increase of available design approaches. Despite this, a central focus is on maintaining and even increasing the ease-of use through restructuring, homogenisation and simplified methods. Nevertheless, similar to the changeover to the first generation of EN 1995-1-2, an additional learning and training process will be necessary, which should start before the final publication.

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FORUM WOOD BUILDING BALTIC

DESIGN FOR MANUFACTURE AND ASSEMBLY

The future of timber construction facing the challenges of Industry 4.0
Dr. h.c. Heinz Köster

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ELEMENTerial – Construction system study for CLT offcuts
Siim Tuksam, Sille Pihlak

The future of timber construction facing the challenges of industry 4.0

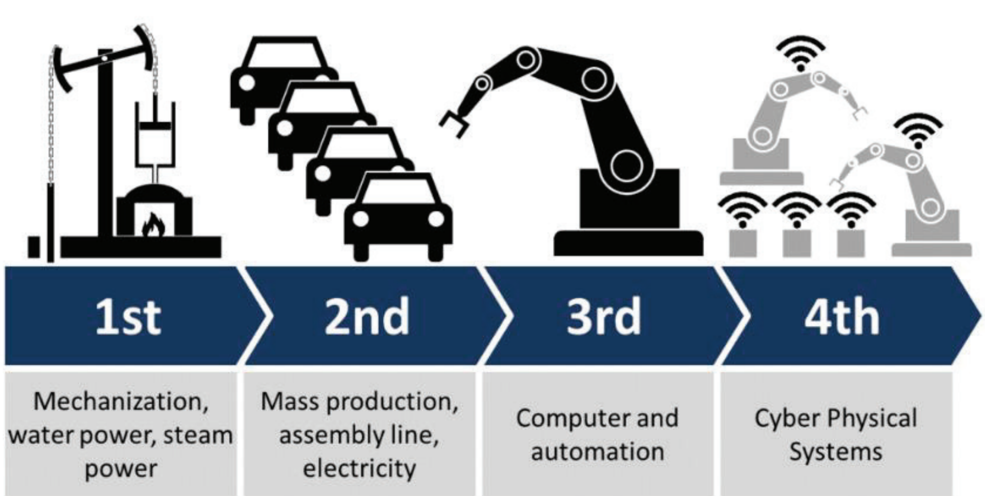
Prof. Dr. h.c. Heinrich Köster, President[1]

[1] Technical University Rosenheim (DEU), Germany

[2] Forum Wood Building

Introduction

Industry 4.0 and the fourth industrial revolution are terms that we have been encountering on a daily basis for several years now. Industry 4.0 refers to the networking of information and communication technologies in industrial production. The aim of this networking is to automate production and enable a direct exchange between man, machine and product in real time. Not just a single step in production is to be optimized, but the entire value chain. The entire life cycle of a product is integrated: Idea, development, production, maintenance, disposal or reuse:



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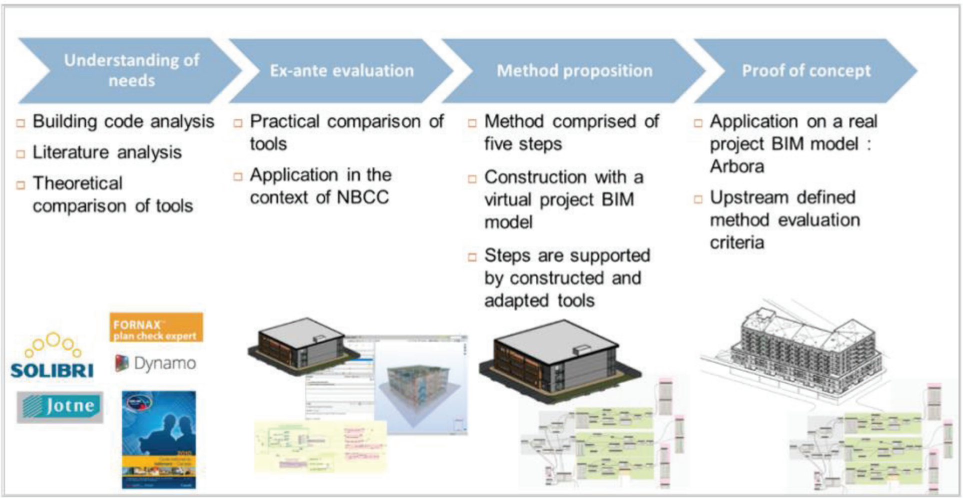
Industry 4.0 in the Wood Building Industry

The aim of Industry 4.0 to robotic prefabrication in timber construction is to develop new production processes that will initiate a paradigm shift. Adaptive and material-efficient construction systems are to be developed through the integration and interaction of computer-based design methods, static optimization, digital production, robotic assembly and quality assurance. The focus is not only on additive manufacturing steps, but on all aspects of cyber-physical production: subtractive manufacturing of individual parts, additive assembly of components into prefabricated assemblies through digitized identification, handling, placement and joining of components, intelligent logistics, feedback and quality assurance. The focus here is not on full automation, but on a "sliding degree of automation" that enables the strengths of craftsmanship and robotics to be combined.

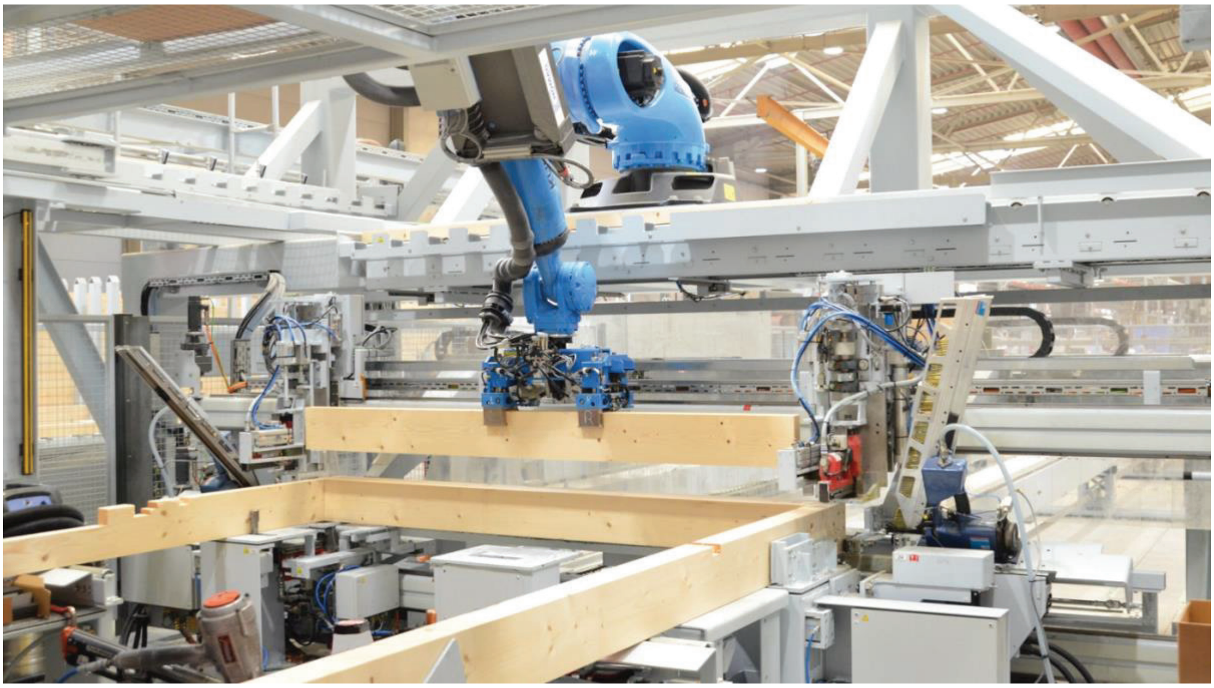
Building Information Modelling (BIM)

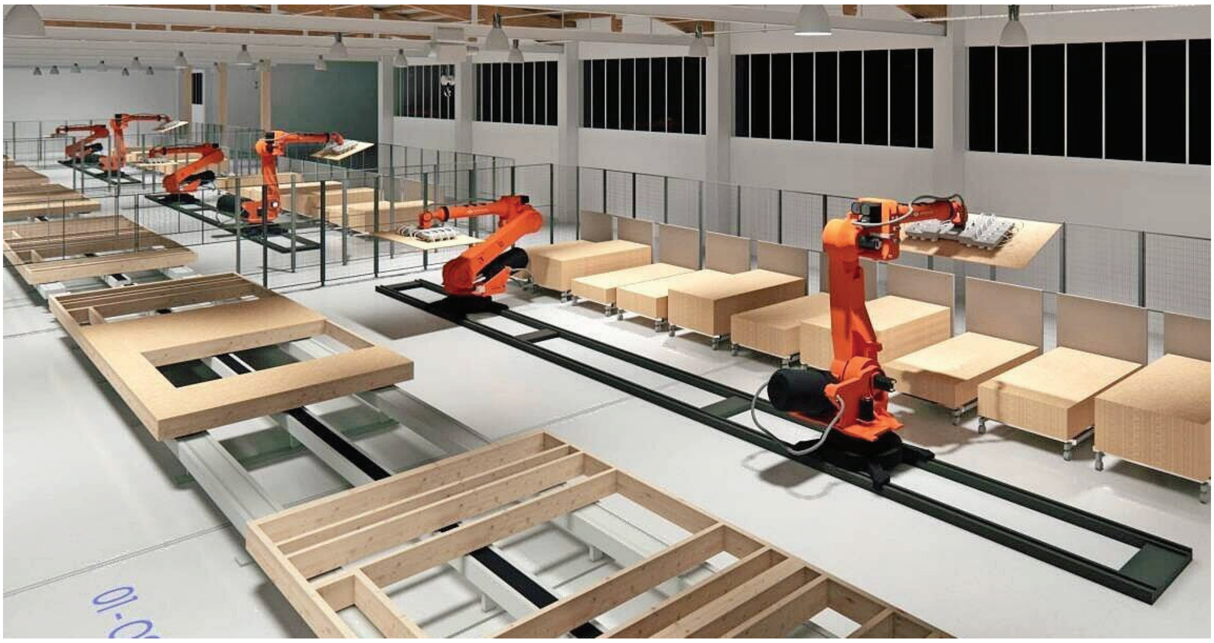
BIM is developing solutions for the value chain of planning and building with wood against the backdrop of digital transformation. It is based on Building Information Modeling (BIM) as a key technology in Architecture, Engineering and Construction (AEC) with far-reaching effects on common working methods. The research project focuses on the further development of methods, tools and actions in prefabricated timber construction to improve smooth planning and data management processes.



Manufacturing

In timber construction, manual work is increasingly being taken over by robots. The main advantages are cost reduction, humanization of the workplace, flexibilization of rigid standard working hours, increased productivity and thus securing skilled workers.





Concept building designs for DfMA with timber

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Summary

This paper concludes findings from a research project, in which a concept guideline was developed for timber office- and residential buildings. The research included practical development research with cross-discipline professionals, with the aim of finding solutions to multivariable problems in timber buildings. Factors such as material efficiency, optimal design spans, floor vibration, flexibility of the floor plan, optimal product utilization and construction site efficiency were considered.

The design optimization process of a conceptual building was systematized and analysed to obtain applicable learnings for future timber buildings, that can be practically used in a DfMA methodology. By means of iterating on a design process, key early design stage decision factors were identified, which significantly affect material and cost and carbon efficiency in the outcome of the design process and the built object. This process has led to a set of ideas and principles that can be followed again when other projects, with different geometries and under different conditions, to practically apply the DfMA methodology for a practicable, material efficient, cost-effective timber-based design. The resulting concept designs and principles have been published at the platform www.buildingconcepts.storaenso.com to disseminate the learnings and support the growth of timber construction.

Key words: Timber buildings, DfMA methodology, material efficiency, optimal design spans, floor vibration, construction site efficiency, design optimization, structural design.

1. Introduction

1.1. Current scenario

The construction industry has seen a significant shift towards the use of timber in multi-rise residential buildings and office buildings. The need for sustainable and low carbon construction methods and materials have pushed even the most traditional actors in this sector to evaluate the use of wood as a mean to reaching their sustainability goals and agendas. In this scenario, many companies in the AEC sector are rethinking their processes, knowledge base and supply chains, looking at implementing timber construction in their standard portfolio, at scales that had not been seen before.

The timber sector has been developing strongly but is perhaps not in a maturity level as industry that will allow it to supply buildings at the required scale, cost certainty and normalized method.

This paper aims to identifying and formulating DFMA principles that can be used to optimize the design and delivery processes, to tackle some of its challenges and make it more competitive. Moreover, the industry has proven to know how to deliver cost competitive, high quality and large-scale projects, but seems to lag in its ability to scale them up and replicate with a higher level of replicability. In other words, the industry seems to face every new construction project as if it was the first of its kind.

A certain level of common understanding in the beginning of a project about how to achieve a practicable and efficient design, could help designers and stakeholders make smarter decisions that are more suitable to wood as a material, aligned to the manufacturing capabilities, and more efficient to assembly. Therefore, the challenge seems to be on what principles and design solutions need to be adopted in the design stage for a successful manufacturing and assembly.

The application of DFMA principles in timber construction projects presents a significant challenge, as designers often lack the experience or detailed know-how to make early design choices that are favourable to wood and its construction value chain. Early design choices have a significant impact in the following design phases, the construction process, and the final built result, and their impacts are not evident from the beginning. Design decisions and choices that are not well aligned with manufacturing and assembly capabilities result in increased complexity and loss of efficiency, impacting negatively on the project´s cost effectiveness.

This paper will address the following question: Is it possible to describe principles and early design choices that can be implemented in a DFMA methodology?

The main hypothesis of this paper is that by the application of DFMA principles, we can find a way to deconstruct a certain effective construction technology, which is normally the result of design process, in conceptual principles and parameters that can be communicated and applied before a design process is started.

Overall, this paper aims to provide a comprehensive overview of the current state of the art in timber construction and the application of DFMA principles, highlighting the challenges and opportunities presented by this approach to building design and construction

1.2. Present research

Current research if often studying optimization of single parts of the system rather than the system itself. In contrast, this development project is about applied research – intends to bring the best practices to timber construction and producing a set of tools and guidelines for efficient timber construction to be used in the early design phases, specifically in the concept design phase.

Current research has shown that the application of current standard design processes have a great amount of, what is described as "friction". This friction is perceived as the need to re-design a project several times along the planning process to adapt it to manufacturing and assembly processes along the project. As described by Schuster and Stieglmeier [1] (Sandra Schuster, 2018): *"In daily planning practice prefabricated timber construction faces numerous shortcomings:*

- *Higher planning efforts because of friction losses between architectural and expert planning from the different disciplines.*
- *Workaround planning and double planning because of late decisions or misunderstandings in interdisciplinary communication...*

… *If expertise in wood construction is lacking at the early design stage, a "re-design" phase is often required after awarding the contract. A further complication is that timber construction companies often have specific characteristics such as production method, level of experience, planning competence and the supply network that can influence the construction.*

This "friction" [2] (Frank Lattke, 2016) impacts costs on a direct and an indirect level: all redesign and adaption is costly. Also on an indirect level: last minute changes on design lead to restricted decision alternatives, and to "least bad" decision making. Furthermore, it´s always too late in the adaption process, which is always against time, to reformulate the project initial ideas.

This and other studies highlight the importance of including detailed knowledge of the manufacturing and assembly processes in an early design stage [3] (Geier, 2017). However, this often finds two limitations in practice:

- In an early phase of the projects, main professionals involved are architectural and structural designers, often starting design without a decision being made towards the material and much less so the manufacturers and installation companies who will deliver the projects. Therefore, knowledge about the material and the manufacturing and assembly processes cannot be considered.
- Procurement law and competition regulations and contractual design & build and design-bid-builds methods assume that there is competition between manufacturers and suppliers after the main concept decisions have been made. Therefore, the specific 'M' and 'A' know-how of the suppliers cannot be included in this phase.

This effect can be described in a simple but often heard phrase when projects are facing difficulties: "if I would have only known this in the beginning of the project, we would have not had this problem in the first place". These difficulties are often perceived as overwhelming complexity.

Systematic solutions have been searched and develop in the past, and there are many great examples of it. Most of them aim at developing build-ups, their connections, and details, as an attempt to integrate them to the DFMA method. They aim at incorporating DFMA principles in the "detail design phase" according to RIBA plan of work. These solutions tend to fail because:

- when a project has passed the "concept design stage" with a geometry and decisions that are not compatible to these details, the process of adapting the technology is too complex and costly.
- they tend to be manufacturer specific, referring to a specific supply chain and preferences which make it difficult for other providers to adapt to. These can be considered closed systems.

Table 1. General DfMA principles.

No.	DfMA Principles	Source
1	It is necessary to prevent unnecessary reworking through error-free design, and to ensure safety and quality during the manufacturing process.	[15–19]
2	It is necessary to minimize waste, through design that considers re-usability.	[17]
3	It is necessary to prevent errors during the process of product handling and assembly, through design that considers production environment and process.	[15,17]
4	It is necessary to reduce manufacturing time and cost, by avoiding complex assembly methods, through design that considers ease of manufacturing.	[15,17–20]
5	It is necessary to reduce the time and cost consumed for the handling process, by simplifying the method of handling and assembling parts.	[15,17–20]
6	It is necessary to reduce the time and cost consumed for the assembly process, by performing design based on the assembly method.	[15,17,19,20]
7	It is necessary to simplify design through modular design.	[15,17–19]
8	It is necessary to minimize manual labor, and secure product quality and assemblyefficiency, through a design that applies a mechanical assembly method.	[15–17,19,20]
9	It is necessary to reduce the time and cost consumed for purchasing parts, through design that repeatedly uses standardized parts.	[15,16,18–20]
10	It is necessary to simplify the manufacturing process, by repeatedly using similar materials.	[15,19,20]
11	It is necessary to minimize the impact on the environment, through the selection of environmentally friendly materials and the minimization of waste.	[16,17,20]
12	It is necessary to reduce the time and cost consumed for the manufacturing and assembly process, through design with a minimum number of parts.	[15–20]
13	It is necessary to reduce the time and cost consumed for the manufacturing process, by standardizing connector types and minimizing the number of connectors.	[15–20]
14	It is necessary to reduce component failure, by minimizing the use of fragile components.	[15,19,20]
15	It is necessary to reduce time and money consumed for the manufacturing process, by minimizing finishing work.	[15,17,19,20]

Figure 1: General DfMA principles as proposed by Seoyoung Jung and Jungho Yu [4] (Seoyoung Jung, 2022).

Extensive literature can be found on the topic DfMA, and most of it can be used to describe these challenges. The definition used by this study was proposed by Seoyoung Jung and Jungho Yu [4] (Seoyoung Jung, 2022):

"DfMA is a concept that has been developed to minimize design changes in the manufacturing industry. DfMA is a design approach that prevents possible errors, in advance, in the production and assembly phases, and improves production efficiency by inspecting various circumstances related to the product production phase in advance of the design phase."

It proposes the following DfMA guiding principles. In this study, they have been used to systemize and organize the learnings obtained from the concept.

2. Methods

The methodology used in this paper takes a holistic approach to building design and construction, considering the interplay between architectural typologies, technological solutions, and the application of DFMA principles. By combining these elements, the methodology provides a comprehensive approach to the design and construction of timber buildings that is optimized for the use of DFMA principles.

This study iterates the design process of a timber structure for a typical project. After each iteration, the design is evaluated on its suitability for manufacturing and assembly from specific suppliers in the value chain. A new iteration goes back to the early project decisions to improve them.

A specific modular kit-of-parts was chosen in a way to rationalize and parametrize the timber components, namely the Sylva Kit by Stora Enso along with its standardized build-ups.

The exercise starts with a residential and office building projects that have been identified as standard. The degree of design freedom has been increased in each design optimization cycle: in the first iteration, a timber option is proposed for the precise floorplan and geometry of the specific project. In the second iteration, it has been allowed to make architectural adaptations to the design of the building. In the third and final iteration, the architecture can be reformulated completely if the same customer requirements are met.

This method results in design principles applicable to many projects of its category.

Overall, iterative methodology used in this paper provides a new approach to building design and construction that is suitable for timber buildings and considers the requirements of multi-rise residential buildings and office buildings. The findings from this methodology will contribute to a better understanding of the impact of DFMA principles on the design and construction process of timber buildings and will provide a framework for the future design and construction of timber buildings.

This paper describes the process of the applied scientific approach for developing the concept. Additional consultancy is received from leading experts from Ramboll Group and Stora Enso. The field of reference for this project was selected to be the Finnish regulation, because in previous studies there has been notions that on some important specifications (such as vibration) the Finnish local requirements seem to be strict.

3. Results and discussion

3.1. Project iterations

The design phase of the project was iterated in the three proposed stages. The design process was carried out from beginning to end three times, identifying with precision which design decisions and choices have which impact the result the most, to be able to go back and change them, in a way that is usually not possible in a real project due to the time constrains. The iteration phases are summarized:

First iteration: choose a building reference case that represents the target markets, its patterns, customer, and technical requirements, and looks. Close collaboration to potential customers was a key, as they could identify these patterns easily as it is part of their daily work.

The customer proposed a reference project and the first step in this process was to identify the typical requirements and challenges associated with different architectural typologies. Through this analysis, patterns were identified within these typologies that formed the framework of a concept for timber building design and construction.

The next step was to apply a library of off-the-shelf prefab timber products. This process involved iterating the necessary build-ups and details to form a singular solution that conforms to the developed concept and meets the needs of typical buildings.

The intervention to the project was only to the detailed design phase, trying to adapt is as little as possible, mimicking what would happen in a real project.

Second iteration: in close collaboration with the customer, the project was adapted and modified as much as necessary to make it adequate for the Sylva kit. The following aspects were modified:

- Structural frame and spans
- Procurement strategy (how the building is broken down to contractual items that can be procured and delivered by local contractors)

But the essence of the project was not changed, only adapted.

Third iteration: The project was started again with a full degree of freedom: how would this project be conceived, if we applied the design strategy that we developed in the second iteration from the very beginning of the project?

By the identification of the what and the how of how this project should now be started, we have in fact created the principles of the concept. And applying these principles in a design process is DFMA.

3.2. Main identified design factors

The design process for the timber-based building project was a three-phase approach, starting with the predesign phase and followed by two iterative adaptation phases. The goal of the design process was to evaluate the economics, carbon efficiency, and user adequacy of the building design while incorporating the use of timber technology.

Main design factors identified in the 1st phase

As a result from this phase, we concluded that the chosen technology adapted to the project did not fit well. There were several compromises and special manufacturing requirements resulting in a costly project lacking the actual benefits of timber construction.

Challenges and learnings from the design process.

1.- The geometry is not ideal for prefabrication, and do not follow the standard dimensions and limitations of manufacturing, transport, and assembly.

2.- Solutions were found for the floor spans in the reference projects, but the solutions tend to be to material intensive or costly, too high construction height or both.

3.- Level of industrialization is difficult to increase unless major changes to the design are made.

Specific to Residential case:

- Floor panels are too thick, affecting the overall cost effectiveness.
- CLT external walls are not commonly pre-fabricated, therefore no significant gains can be made without significant changes in the value chain.
- As a result of the above we need a tent (Finland)

- No suitable floor build-up (for these customers in Finland) to leave ceilings uncovered.
- Floor to floor height does not match manufacturing standards impacting material and cost efficiency directly.

Specific to Office case:

- Spans are too long for timber floors:
- An installation layer for MEP and HVAC makes this problem much worse if under the main beams or created the need to extremely challenging penetrations in the structure.
- Floor depth increases to a point where a floor is lost and the economic viability of the project is questioned.
- Simple addition of columns does not suit the architectural design

Main design factors identified in the 2nd phase

The iterative adaptation phases (2nd phase and 3rd phase) involved the initial step of adapting the design to fit the customer demands and applying the Design for Manufacture and Assembly (DfMA) methodology in practice. The design was then reformulated based solely on the available kit-of-parts. Through this process of elimination through design iterations, the best possible solution was reached.

All changes to the architectural design were discussed with the customer as necessary adaption to the existing. Dimensions of the frame and architecture were adapted to fit the foreseen manufacturing and assembly processes.

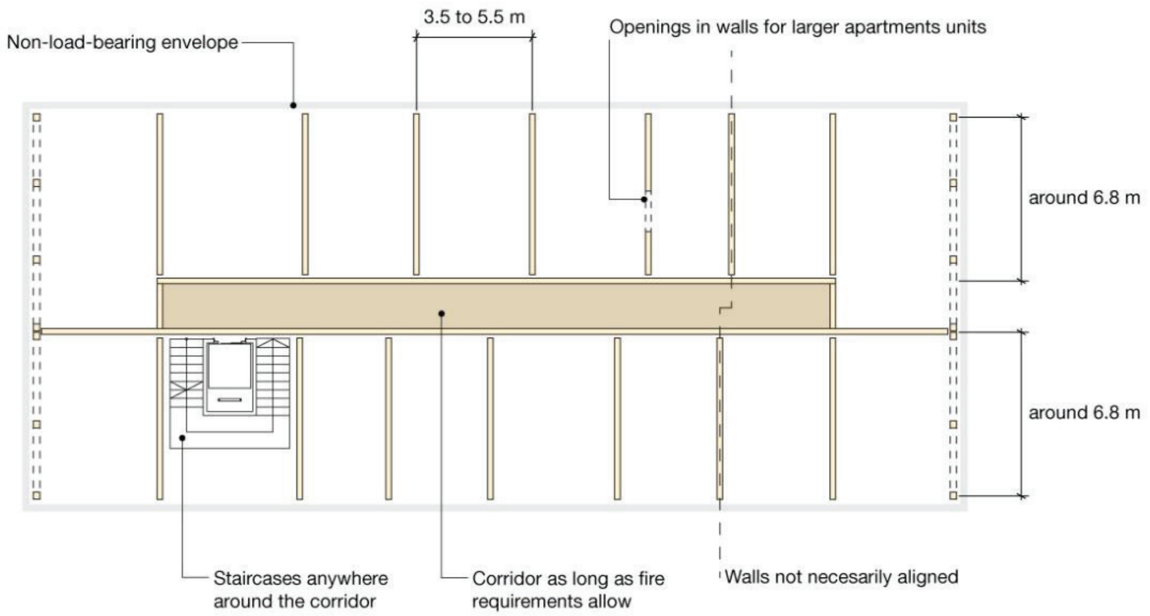

Figure 2: Multi-storey Residential Building Concept, schematic main design principles. Further details at:www.buildingconcepts.storaenso.com

Challenges and learnings from the design process.

1.- The structural systems were reformulated completely, although not changing the basic geometry of the original project.

2.- Dimensions were adapted to match better manufacturing limitations and assembly processes, based on the Sylva-kit by Stora Enso.

3.- A strategy was found to maximize the level of industrialization, separating envelopes from main structure.

Specific to Residential case:

- Found an industrialization/ procurement strategy that suits the customer and the value chain in its market: load bearing internal frame and non-load bearing highly prefabricated timber frame envelope as produced by local industry.
- Load bearing compartment walls at distances that are effective in timber construction.
- Where the above not possible, introduce intermediate support structures of beams and columns.
- Balconies proposed as self-supporting structures.

Specific to Office case:

- “negotiated” reasonable grid for timber and office standard layouts.
- Introduce corridors without down-standing beams for main MEP and HVAC main distribution lines. This requires adding a column line between the corridor and the working space.
- Modified core position to match proposed grid (not very successful adaption of the geometry, as generates problems with daylight and adaption to site)
- Add main beams in working spaces in a way that they are acceptable from the structural depth and an architectural feature in the working space.

The adaption of the technology was “difficult” a lot of compromises had to be done on both ends: barely acceptable from the design perspective and “less than ideal” to manufacture and assembly.

This underlines that the process will always include friction, but the DfMA-strategy shifts the friction into a stage where the problems can be addressed with minimal costs and an acceptable compromise can be achieved.

Main design factors identified in the 3rd phase

The 3rd phase in the design and application of solutions resulted into a process of elimination through design iterations to find the best possible solution. After a solution was reached, we extrapolated the design so that it creates a ruleset which results in a concise concept design guideline.

General strategies outlined in this phase:

Define timber construction concept and principles optimized for manufacturing and assembly based on the following ideas.

- Based exclusively on an off-the-shelve kit-of-parts, along with its associated application technology (build-ups, connections, etc)
- Using dimensions of the standard recommended product ranges, how they affect an architectural layout.
- Limiting floor spans
- Integrating a strategy for MEP and HVAC distribution.
- Develop HVAC and MEP concepts, to determine the above integration strategy.
- Break down the building design into procurable packages that fit the local value chains and customer preferences. Design should allow a clear cut and minimize interdependencies between these trades.

3.3. Proposed design principles and strategies.

Main strategies for the residential building:

- Structural conceptual design based on the principle of parallel internal and compartment load bearing walls, defining minimum and maximum distance between them to determine main spans.
- Apartment library which is based on this structure and ruleset.

- Beam and column system on the gables to allow the frame to be installed independently of the façade.
- Non-load-bearing façade that can be installed after the frame is installed, highly prefabricated, aligned to local manufacturers.
- Self-supporting balconies.

Main strategies for office building:

- Pure timber solution
- Propose and effective timber grid, which fits the local office space modulation.
- Structural system that minimizes the main span, to assure cost-competitiveness, based on local vibration requirements.
- System to avoid perforations to beams: Propose a "racing track" strategy around stabilizing cores without down-standing beams

Summary

The outcome of the design process was a ruleset, which resulted in a concise concept design guideline for the timber-based building. The design process allowed for the optimization of the timber technology kit-of-parts to meet the customer demands while considering the economic and environmental factors. The final design not only met the functional requirements of the customer but also incorporated a high level of sustainability using timber technology.

In conclusion, the design process for the timber-based building project was a comprehensive approach that considered the economic, environmental, and user-centered factors. The use of the DfMA methodology and the iterations in the design process resulted in a well-optimized and sustainable building concept design.

Considering the previous highlights, the principles and strategies developed for the architectural and structural design of both residential and office concepts. The design was optimized for material use and based on an off-the-shelf kit-of-parts, which assured the availability and pre-optimized components. The design principles and strategies were developed to meet the most common customer demands and relevant technical requirements.

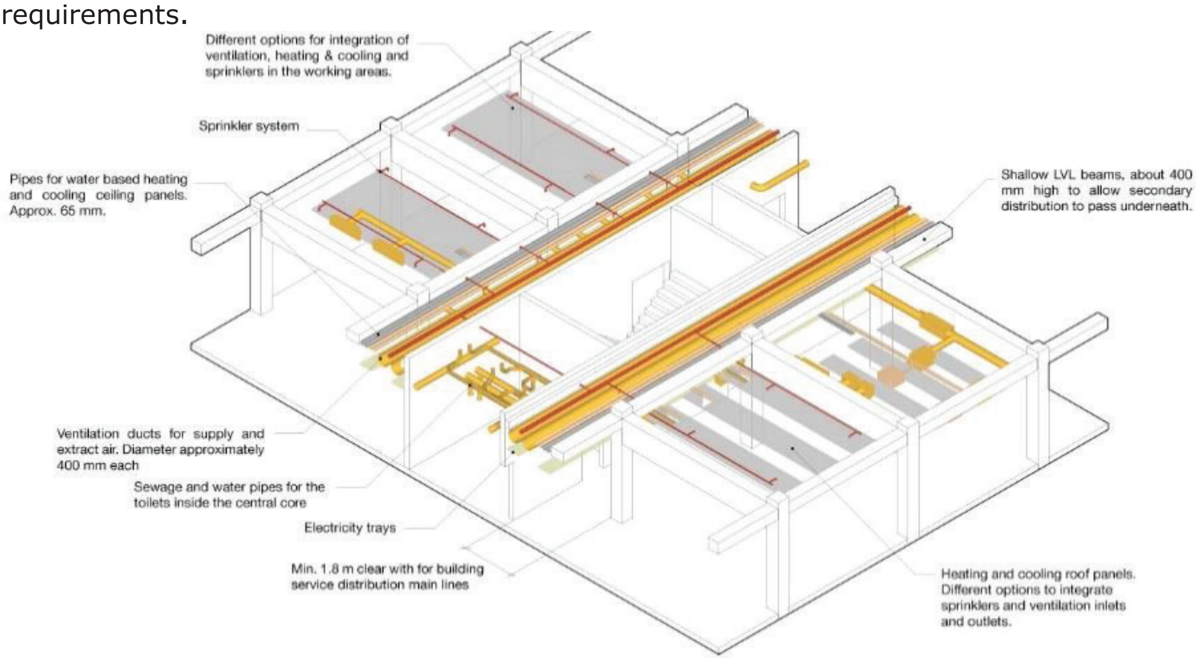

Figure 3: Office Building Concept (22m wide), schematic main design principles. Further details at: www.buildingconcepts.storaenso.com

The residential concept was material-optimized to fit the manufacturing and building processes, and the design was modified to minimize the use of wood in the floor by finding an architectural design that fits an optimal floor span. The design also aimed to maximize the level of industrialization based on parts and pieces that are widely available in the market, due to its design that allows for it.

3.4 Application of DFMA principles.

Following the DFMA principles cited above, the developed concepts propose the following strategies.

1. It is necessary to prevent unnecessary reworking through error-free design, and to ensure safety and quality during the manufacturing process.

The concept proposes to work with kit-of-parts with clear guidelines and rulesets for each to assure optimal manufacturing.

2. It is necessary to minimize waste, through design that considers re-usability.

Modular and dimensional constraints are clearly stated where necessary, indicating flexibility wherever the system allows.

3. It is necessary to prevent errors during the process of product handling and assembly, through design that considers production environment and process.

The use of a prefabricated kit-of-parts with its design ruleset assures that the manufacturing and assembly processes are considered in the architectural design.

4. It is necessary to reduce manufacturing time and cost, by avoiding complex assembly methods, through design that considers ease of manufacturing.

A basic proposed principle is to design based on separate functional packages, which can be procured and installed separately on site, reducing by design interdependencies to the minimum.

5. It is necessary to reduce the time and cost consumed for the handling process, by simplifying the method of handling and assembling parts.

The parameters and rulesets for the design of the elements are determined by the kit-of-parts, which are optimized not only from a manufacturing point of view, but also for their handling, transport to site and installation.

6. It is necessary to reduce the time and cost consumed for the assembly process, by performing design based on the assembly method.

The concept is designed to use elements as large and standardized as possible, to reduce the number of parts to install.

7. It is necessary to simplify design through modular design.

Modularity is tackled using the standardized kit-of parts, which balance to degree of geometrical freedom and the requirements for modular manufacturing. The effects of these to a building geometry are clearly explained in the concept explanatory drawings.

8. It is necessary to minimize manual labor, and secure product quality and assembly efficiency, through a design that applies a mechanical assembly method.

All parts have been designed to be installed with standard cranes and assembly methods.

9. It is necessary to reduce the time and cost consumed for purchasing parts, through design that repeatedly uses standardized parts.

Using a kit-of-parts from a manufacturer simplifies the procurement and purchase processes significantly.

10. It is necessary to simplify the manufacturing process, by repeatedly using similar materials.

Using a kit-of-parts

11. It is necessary to minimize the impact on the environment, through the selection of environmentally friendly materials and the minimization of waste.

Use of a renewable and low-carbon material and modular kit-of-parts minimizes environmental impact and waste to nearly zero.

12. It is necessary to reduce the time and cost consumed for the manufacturing and assembly process, through design with a minimum number of parts.

The rationale of the modular use of construction parts helps minimize the number of parts.

13. It is necessary to reduce the time and cost consumed for the manufacturing process, by standardizing connector types and minimizing the number of connectors.

Specific connectors are not part of the concept, as it is considered that this is defined in a later stage in a detailed design phase. The concept, however minimized the types of connections, which reduces the need for using different types.

14. It is necessary to reduce component failure, by minimizing the use of fragile components.

The concept combines different technologies and components that have been tested and follows the limitations and recommendations for each one.

15. It is necessary to reduce time and money consumed for the manufacturing process, by minimizing finishing work.

4. Conclusions

It has been observed, that through a long process of iterations, the design of the prototype projects changes significantly, although not its functionality. It can be argued that the initial and the final designs are the same buildings but materialized in different ways. This exemplifies how the adaption of different technologies, in this case from concrete to timber, can change the final form of the product, but resulting in essence in the same building, fulfilling all its customer requirements and function.

As it can be observed in the application of the DfMA principles, the main benefits are obtained from the use of a standardized platform of parts. If these parts and pieces are optimized for the manufacturing and assembly process, by its correct use, the overall result will most likely be well suited for DfMA.

In this sense, we can conclude that the application of the DfMA principles is not possible, or not effective, for designs that are not created considering it from the beginning. Moreover, the DfMA methodology will only be successful if a project is conceived from the early beginning with a determined platform or kit-of-parts, which is used during the project to create its form.

The concepts developed also describe principles and rules on how combinations of these parts can perform or be suited for different types of buildings, in a way to solve problems that are usually first detected in later stages of the design process. These principles, in a way, condense the learnings or a long optimization process which is normally not possible in standard unidirectional projects.

These concepts describe principles on how to create structures for one specific set of needs of residential buildings, and one office typology. Different building typologies will result in different principles and different combinations of components.

The main challenge remains to include this kit-of-parts from the very start of the project, and that these remain stable during the design process. It is clear from previous research findings, that the choice of a precise kit-of-parts or platform is not always possible due to restrictions in competition law, or because the investors wish to remain neutral to the supplier choice. These factors remain a deterrent to the application of the DfMA in current practice.

5. Acknowledgements

The development of this concept was financed by Stora Enso Building, Building Solutions, in partnership with Ramboll and Wood Expert. The technical development of the Building Concepts itself is the result of the collaboration between several employees of the aforementioned institutions, and not exclusively from the authors of this paper. The development was inspired in a collaboration project between Combient Pure, NCC Finland, Ramboll and Stora Enso.

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ELEMENTerial – exploring architectural potential of CLT fabrication residues

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Summary

The purpose of the project was to suggest a possible method or a potential product valorising CLT fabrication residues. Producing construction elements from CLT results in ~10% residues, mainly doors and windows. Their odd size – neither log nor wall – allows for the exploration of mid-scale tectonics. A design algorithm for intuitive manipulation of pre-optimised geometries was used. The result was a functional shelter structure of considerable architectural qualities, demonstrating an adaptable building system, based on repetitive elements. Due to the single step optimisation of the building-blocks the product is not yet commercially viable and needs further investigation.

Key words: Building system; Algorithmic architecture; Valorisation of fabrication waste; Pre-fabrication; Design automation. (3-7 keywords are required, must fit on two lines)

1. Introduction

The Estonian timber industry is one of the biggest exporters of cross laminated timber (CLT) elements and timber houses in Europe.[1] Thus the actions taken in maximising the value of the materials has been important. With the growth of timber construction industry in Estonia, there is also an increase in industry residues, summing up to 10% of the all used CLT. The aim of the project was to suggest a possible method or a potential product that would valorise the waste material. When cutting out wall elements from plate materials there are often leftovers such as window and door openings. This residual material allows the wood to be seen as mid-scaled building blocks – neither log nor a whole wall, creating a possibility for novel mid-scale tectonic solutions to be explored.

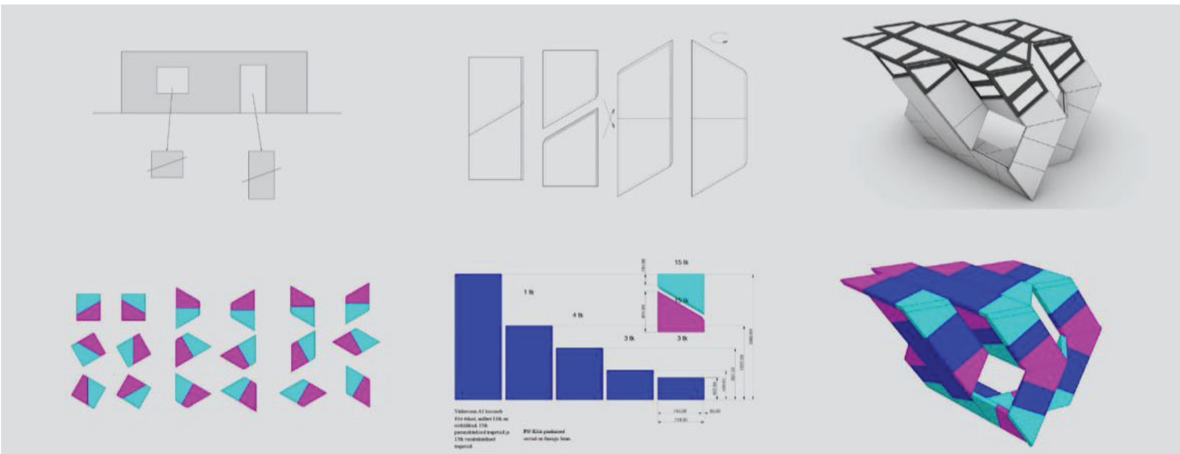

Figure 1 ELEMENTerial strategy exploring the usage of CLT cut-outs as discrete timber building blocks.

[1] https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Wood%20Sector%20in%20Estonia_Warsaw_Estonia_12-20-2016.pdf

2. Methods

Standard elements were developed that can be cut from average production remainders and offer designs based on these elements in the form of small architectural forms. One specific output is, for example, a bus stop, but it can be developed into a structural facade system.[2] For the design of the structure a custom algorithm was developed to automate the design process from form finding to production drawings.

3. Results and discussion

The result was a functional shelter structure of considerable architectural qualities, demonstrating an adaptable building system, based on repetitive elements.

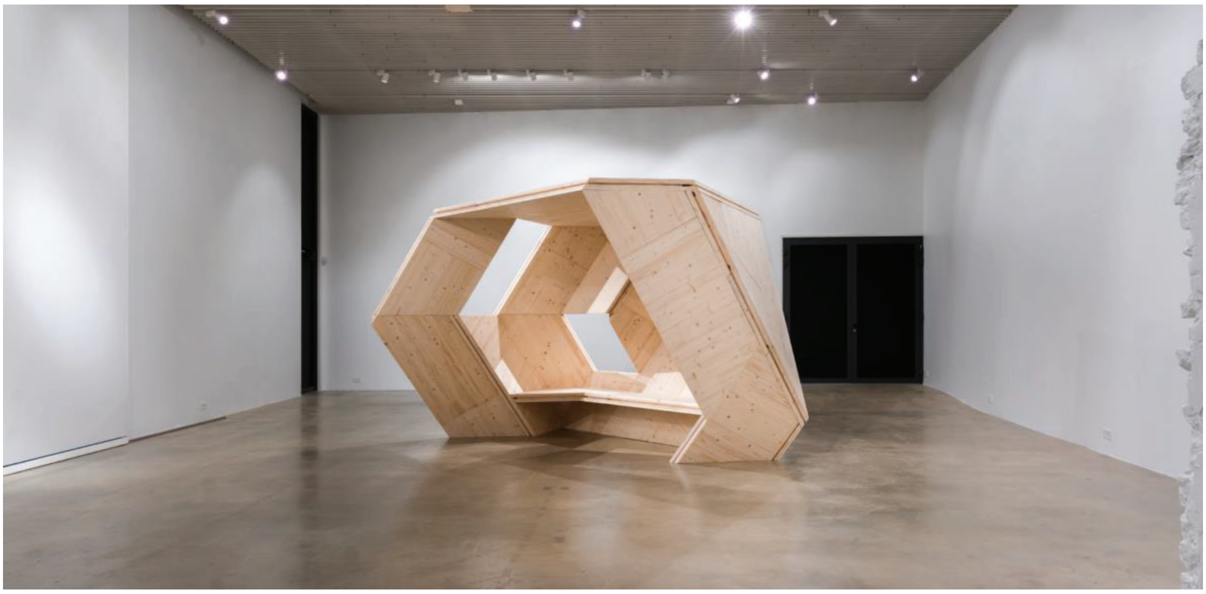

Figure 2 ELEMENTerial bus stop in Estonian Academy of Arts gallery. Discrete elements allowed to construct walls, roof, openings and a bench out of one kind but variable length elements. Photo: Johan Huimerind

This prototype was an investigation into timber house manufacturing leftovers, which raised multiple further possibilities in standardised element based timber construction. Ongoing investigation looks into further automation in standardisation of residual elements and zero-waste material usage strategies in apartment building design.

4. Acknowledgements

Location: previously EKA Gallery, currently Paide city center
Industry partner: Arcwood by Peetri Puit
Project: 2020-2021
Researchers: Sille Pihlak and Siim Tuksam (EKA PAKK)
Engineer: Indrek Mäe (Arcwood)
Fabricator: Arcwood
Fixing systems: Rothoblaas Estonia
Supporters: Eesti Kultuurkapital, Eesti Kultuuriminsteerium, Eesti Kunstiakadeemia Arhitektuuriteaduskond, Eesti Arhitektideliit, Arcwood by Peetri Puit, Rothoblaas

[2] https://woodhouse.ee/wp-content/uploads/2022/09/Elina-Jopiselg-magistritoo-sLenderi-valisseinaelemendi-konstruktsiooniline-lahendus.pdf

FORUM WOOD BUILDING BALTIC

TIMBER BASED RENOVATION SOLUTIONS

Circular renovation of an apartment building with prefabricated insulation elements
Eero Nigumann, Targo Kalamees, Kalle Kuusk, Peep Pihelo
Timbeco Ehitus OÜ (Estonia); nZEB Research Group, Tallinn University of Technology (Estonia)

Development of prefabricated additional insulation elements for the renovation of high-rise apartment buildings
Peep Pihelo, Targo Kalamees
nZEB Research Group, Tallinn University of Technology (Estonia)

Case studies of moisture safety implementations on timber structures
Eneli Liisma, Rauno Lemberg, Erik Sumeri, Daniil Khaustov, Aleksandr Gildi
AS Merko Ehitus Eesti (Estonia)

Commissioning the Design and Construction of Prefab Renovation
Alari Jürgenson, Peep Pihelo
Tallinn University of Technology (Estonia)

Misused timber in renovation
Üllar Alev
Tallinn University of Technology (Estonia)

Circular renovation of an apartment building with prefabricated insulation elements

Eero Nigumann, project manager[1]; Targo Kalamees[2]; Kalle Kuusk[2], Peep Pihelo[2]

[1] Timbeco Ehitus OÜ, Estonia
[2] nZEB Research Group, Tallinn University of Technology, Estonia

Summary

H2020 project DRIVE0 accelerated deep renovation processes by enhancing a consumer centered circular renovation process in order to make deep renovation environmentally friendly, cost effective and more attractive for consumers and investors. Estonian pilot in Saue, Estonia was developed based on the circular economy principles in collaboration of Timbeco and Tallinn University of Technology and renovated by Timbeco. The goal was to carry out the project in the shortest possible time and to use prefabricated insulation timber frame facade elements. The façade elements were designed on the principle of circular design in such a way that, if desired, they could be reused in new renovation projects or in the construction of 1-2 storey townhouses. Based on the measurement, real energy use after renovation represent the highest energy performance indicator

Key words: Circular renovation; Prefabricated insulation elements; Deep renovation; Design for disassembly; nZEB.

1. Introduction

In Estonia, nearly 70% of the population resides in apartment buildings. The country has a total of approximately 22,000 apartment buildings, predominantly constructed between 1960 and 1990. Approximately 14,000 of these buildings require extensive renovation to align with the objective of achieving a carbon-neutral building stock by 2050.

Based on the European renovation ambition, the plan is to renovate 22% of the Estonian building stock to energy performance certificate class (EPC) "C "by 2030, 64% by 2040 and 100% by 2050. As the renovation volumes increase, there is also a risk of an increase in construction prices. To mitigate this increase, it is reasonable to introduce industrial reconstruction of apartment buildings, which in the long run will keep prices at a reasonable level and, thanks to the scale effect, more projects can be carried out.

2. Design and production of insulation elements considering circular renovation principles

Before commencing the renovation project, a pre-renovation study was conducted to examine the structural reinforcements' locations and fastening solutions' stability on the building. The building was laser-scanned, resulting in a point cloud of the apartment building's facade and surroundings. This data was then used to create a digital 3D baseline model of the building in Autodesk Revit software, providing a foundation for the facade element model's creation.

The facade elements were designed according to the circular design principle in such a way that, if desired, they could be disassembled and reused in new renovation projects of a similar building or in the construction of new 1-2 storey terraced houses (see Figure 1).

In the renovation of the building, insulated facade elements produced in the factory were used (Figure 2). Before the installation, the window openings were also made larger in some rooms. When finishing the facade elements, mass-painted cement board was used, which was combined with wooden cladding. During the production of the façade elements, 66% of the timber frame and horizontal insulation slats were utilized by gluing together the production scraps using the finger jointing method. The old windows were removed and replaced with triple-glazed plastic-framed windows that had been previously installed in timber framed elements at the factory. An external wind barrier and an internal vapor barrier tape were used for the sealing of the windows. The fastenings of element structures are designed in such a way that these elements can be removed from the walls later and used either for the same purpose on another building or disassembled.

Figure 1. A 2-story terraced house project that can be built from recycled facade elements based on the circular economy principle (left). 2-storey terraced house project (right)

Figure 2. A facade element produced in the Timbeco factory before being transported to the construction site (left). Installation of facade elements on the construction site (right).

3. Conclusions

The technical solutions we developed were a success and can be implemented for renovation of same type of buildings and different type of three story buildings. Circular prefabricated modular external additional insulation elements were developed, produced, and installed in a typical apartment building with minimal disruption to occupants due to the shorter construction time compared to traditional on-site renovation. Based on the measurement, real energy use after renovation represent the highest energy performance indicator – EPC “A” = nZEB (nearly Zero Energy Building).

Prefabricated serial renovation has great potential for renovating an entire block of buildings at once. This leads to economies of scale in production and helps to implement the ambitious European reconstruction plan.

4. Acknowledgements

This work has been supported by the European Commission through the H2020 project DRIVE0, by the Estonian Research Council through the grant PRG483, by the Estonian Centre of Excellence in Energy Efficiency, ENER (grant TK230) funded by the Estonian Ministry of Education and Research. Kuuma 4 Saue apartment association is acknowledged by fruitful collaboration before, during and after the renovation.

Development of prefabricated additional insulation elements for the renovation of high-rise apartment buildings

Peep Pihelo, Researcher [1]; Targo Kalamees, Professor [1]

[1] nZEB Research Group, Tallinn University of Technology (TalTech), Estonia

Summary

In the current study, hygrothermal analyses of the existing building envelope and prefabricated insulation elements to be installed were conducted to ensure the compliance of expected renovation results of high-rise apartment buildings. The results confirm that the building envelope of the additionally insulated high-rise building in the cold and moist climate region needs careful hygrothermal design and consideration of material properties to guarantee adequate moisture dry-out and avoid mould growth.

Keywords: prefabricated additional insulation elements; hygrothermal performance; moisture safety; nZEB deep renovation; energy performance

1. Introduction

The EU Renovation Wave Strategy foresees improvement of the energy performance of buildings, minimisation of emissions, and extend the service life of buildings. It is stated that the renovation rates should at least double in the next few decades. The efficient way to meet these requirements is to renovate the apartment and public buildings with prefabricated additional insulation elements. With high-rise buildings, special attention must be paid to higher moisture loads, caused by wind-driven rain before and during the installation of the insulation elements.

2. Methods

The long-term hygrothermal measurements were taken in the different critical spots of the external envelope of the 9-storey apartment house, the calculation model was calibrated, and a series of combinations with prefabricated elements were analysed using building performance simulation software to compare risks and the main hygrothermal properties of the different sets and thicknesses of materials in the insulation element.

The building type studied is a 9-storey apartment building with a total area of 4990 m^2, constructed in Tartu, Estonia in 1989 (see Figure 1).

Figure 1 9-storey apartment building area in Tartu, Estonia (left). Installation of the sensors and prefabricated test elements onto the apartment building studied (right).

The thermal transmittance of the existing envelope before renovation was U = 0.9-1.2 W/(m^2·K). The external walls are to be insulated with prefabricated timber frame additional insulation elements with a total thickness of 330–380 mm, incl. buffering layer <120 mm (see Figure 2). After the nZEB renovation designed thermal transmittance U_{wall}≤0.12 W/(m^2·K), U_{roof}=0.10 W/(m^2·K), U_{window}≤0.80 W/(m^2·K).

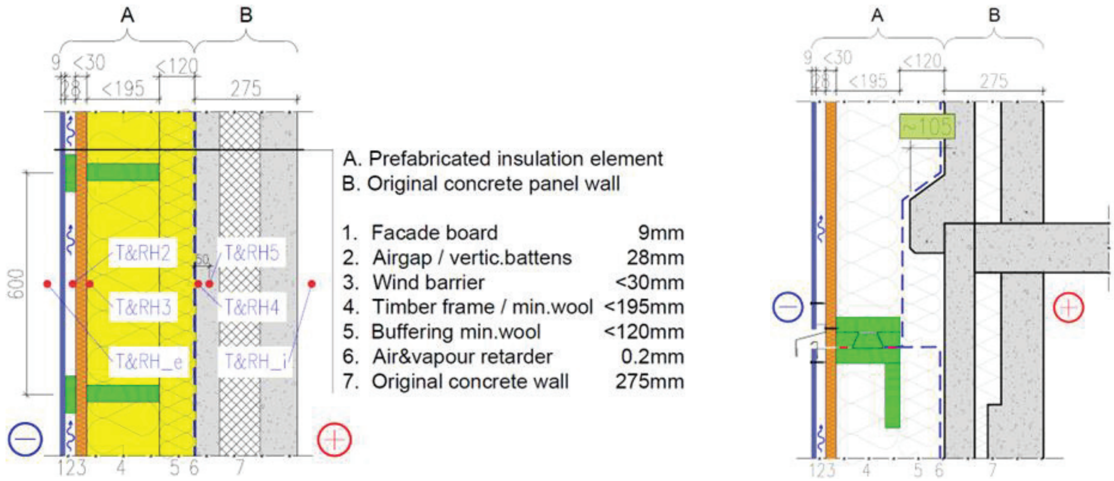

Figure 2 Horizontal cross-section with marks of critical points measured and analysed (left) and vertical cross-section (right) of the prefabricated insulation element on the existing large concrete panel.

3. Results and discussion

Mould index calculations and moisture dry-out analysis indicate an increase in mould growth risk with increasing vapour resistance of the outer layer of elements (e.g., sheathing membrane vs. MW board) and with greater insulation thickness (i.e., with the decrease of temperature and the subsequent increase of RH in external layers of the structure). The initial moisture content of the large concrete panel external wall at the height of the 9th floor (w ≤110 kg/m^3; u ≤4.7%) is drying out down to the equilibrium level (w ≤40 kg/m^3; u ≤2.1%) over a quite long time. The built-in moisture dry-out can last for more than 3 years when the air and vapour control layer's 0.3 m<S_d<0.8 m and about 2 years with a MW wind barrier layer and when the air and vapour control layer's S_d<0.3 m (at RH>85%). There are many buildings with poor thermal efficiency and unsatisfying indoor climate, built decades ago. The use of prefabricated additional insulation elements for its improvement, with a thorough hygrothermal analysis, and following up the routine of moisture safety protocol and integrated design, might be an effective option.

4. Conclusions

For the renovation of external envelopes, the proper solutions are insulation with low water vapour resistance (both for main insulation and wind barrier) and vapour barriers/retarders with low and/or varying vapour resistance. From the perspective of hygrothermal performance, minimal mould growth risks, and better moisture dry-out, the MW board with a special wind barrier facing is the best choice for a wind barrier.

5. Acknowledgements

This research was financed by the Estonian Research Council with Personal research funding PRG483 "Moisture safety of interior insulation, constructional moisture, and thermally efficient building envelope", by project LIFE IP BUILDEST (LIFE20 IPC/EE/000010), and H2020 project "oPEN Labs" (grant agreement No. 101037080).

Case studies of moisture safety implementations on timber structures

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Summary

The focus of this paper is set on moisture safety and its development steps with timber structure buildings on-site during the last five years in Estonia. Cross laminated timber (CLT) and glued laminated timber (GLT) structure public schoolhouse buildings are selected for samples. Chosen construction technology, environmental conditions on-site, design approach in documentation, national requirements, and recommendations for moisture safety during building process are compared. Selected amount of CLT and GLT element moisture content (MC) control measurements for moisture safety target evaluation were performed on-site to monitor the building process risk extent and determine the development of construction culture of timber structures.

Key words: CLT, GLT, Timber structures, Moisture safety, Building technology, Construction quality, Construction culture.

1. Introduction

This survey is based on two case study scenarios with timber structure schoolhouse buildings compared to Viimsi State Gymnasium (VSG) schoolhouse as the first CLT-element usage pilot project. The focal point is set on Pelgulinna State Gymnasium (PSG) and its complexity due to quite large construction area as 3773 m^2, floor area as 8273 m^2 and considerable amount of timber structure usage that is approximately 90% compared to concrete. For a comparable purpose, Rae State Gymnasium (RSG) with construction area of 2700 m^2 and floor area of 4357 m^2 was chosen as a half the size similar example. In case of PSG there was a protective tent for timber structure moisture safety support, however with RSG similar approach was implemented as in VSG where construction was performed without a preliminary roof option. The target of this survey is to compare different moisture safety implementations on timber structure buildings and to give practical on-site learning points from the general contractor's perspective.

Figure 1 Pelgulinna State Gymnasium (PSG) model illustration by Architect Must (left). Rae State Gymnasium (RSG) model illustration by KOKO architects (right).

2. Methods

The method concept of this survey is a comparable analysis of moisture safety requirements stated in the construction documentations and national regulations within last five years in Estonia related to timber structure buildings as a noticeable growing trend in the field. On-site MC measurements of timber structure were performed by pin electrode moisture meter (Extech MO290 and FMD Moisture Meter) with 40 mm pins and compared to upper safety limit criterion for timber structures according to best practice and similar case studies.

3. Results and discussion

Both, long-term and short-term timber structure installation scenarios were under survey with PSG and RSG respectively. The construction of PSG was divided into 3 parts (A, B, C) based on the building's geometry. Due to the building's complicated geometry the tent could not have been placed over the whole building, which caused some direct water contact. The transitioning areas between parts of the building were the most critical areas regarding MC. Initial MC content of timber structures was in the range of 10,5% - 13,4%, but it reached up to 40% in the most critical areas. After 7 weeks being protected by the tent it lowered to 11,5%. Without protective tent cases as in RSG the safe moisture level target took longer time to achieve.

Figure 2 On-site MC measuring of CLT element (left). Construction of protective tent over the first part (part C) on the example of PSG building (right).

4. Conclusions

On constructing large-scale mass timber buildings, a tent can only be used once the assembly of the elements on the whole building or a part of it is finished. Due to this a tent does not provide moisture safety but does help reduce the MC of open CLT elements once the assembly is over. The highest risk factor for high MC in CLT elements is standing water and formation of puddles. High levels of MC were only found in certain areas, where water had collected. From measurements of other panels, even if small amount of water were to get inside the elements' protective cover, it would not cause high levels of MC if it did not stand still for a prolonged time.

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Commissioning the Design and Construction of Prefabricated Renovation

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Abstract

This research addresses the process of reconstructing apartment buildings with prefabricated insulation elements with a focus on their design, production, and installation. The study examines the use of prefabricated insulating elements in the deep energy renovation of apartment buildings in Estonia, to identify the advantages and challenges of this approach and discusses how to optimize these processes. The research focused on the different types of elements, their design, production, site preparation and installation, and post-installation work. In addition, the study analysed the bottlenecks that emerged, and which could hinder an increase in renovation volumes. The study offers a structured guide, detailing recommendations for each phase of the construction process, from designing the elements to their installation and subsequent post-installation work. It touches upon specifics like the importance of sealing barriers and considerations for winter installations.

Keywords: prefabricated insulation elements; deep energy renovation; owner supervision; on-site quality commission

1 Introduction

The reconstruction of apartment buildings is a relevant topic in Estonia, as many residential buildings were constructed during the Soviet era and require improvements in energy efficiency and overall living environment quality. By 2050, Estonia, along with other members of the European Union, aims to achieve climate neutrality. This implies that by 2050, buildings constructed before 2000 should be renovated to at least energy label class 'C', i.e., EPV<150 kWh/(m^2·a) (MKM, 2023). Focusing on apartment buildings, around 14000 apartment buildings in Estonia need renovation (MKM and TalTech, 2020) and almost all comprehensive reconstructions are carried out with support from the KredEx state-owned foundation. In 2023, within the KredEx support round, 212 support applications were initially submitted (KredEx, 2023), but not all of them will receive funding for renovation. Considering about 200 apartment building renovations are finished annually, this number needs to be more than double to achieve expected building renovations by 2050 (2020/662/EC, 2020). One solution to increase volumes is the reconstruction of buildings using prefabricated insulation elements. The optimal design and preliminary planning of building works are essential parts of the construction process. It is critically important for deep energy renovation of apartment buildings, where, in addition to installing new construction components, challenges and obstacles related to the existing building must be faced and overcome.

The objective of this study is to investigate the reconstruction process of apartment buildings using prefabricated insulation elements, focussing on their design, production, and installation. The work addresses the use of prefabricated insulation elements in the renovation of apartment buildings in Estonia, aiming to determine the benefits and challenges this approach offers and how to optimize these processes. The collaboration and roles of designers, owner supervision, and renovation experts, along with building owners and construction subcontractors, besides fulfilling contractual obligations, should be based on detailed and comprehensive studies, drawings, and instructions. This contributes to smooth, high-quality results achievable within a reasonable timeframe and budget. A significant part of the study is devoted to analysing practical challenges faced on construction sites, which stem from incomplete preliminary investigations or design lapses. Notable challenges include issues with girders due to unverified subsoil strength and difficulties with lifting equipment resulting from unanticipated soil resistance. These real-world problems necessitated improvised solutions, such as the introduction of glulam beams or the replacement of temporary soil. The research also sheds light on problems associated with inadequate use of point-cloud data, such as misaligned or defective elements, which then require extra on-site adjustments.

2 Methods

The research took place in the Estonian cold and humid climate during the winter and spring periods when challenging weather conditions affected the construction processes. The design and building preparations were monitored and installation works were supervised with deep interviews with contractors on 5 different building projects in Estonia in 2023 where in the process of deep energy renovation, the prefabricated insulation elements were installed onto the existing multi-story apartment buildings (see Figure 1).

Figure 1 Monitored apartment building renovations with installation of the prefabricated elements in Estonia, Tartu (left), Sindi (middle), and Pärnu (right).

To gather data, on-site observations were conducted, during which random inspections of building sites were carried out and participation in construction meetings and discussions took place to gain practical experience and information directly from the construction site.

Figure 2 References of pilot projects supported by KredEx in Tallinn, Akadeemia 5a (photo by Postimees, 2017) (top) and in Saue, Kuuma 4 (photo by Ansvar Projekt, 2021) (bottom).

In addition to the literature review (ByggaF, 2013; Hienonen et al., 2017; Pihelo and Kalamees, 2021, 2019; Ruud et al., 2008; Wallenten and Mjörnell, 2019), and interviews conducted with various participants of construction projects such as designers, builders, owner supervision, element manufacturers and installers, manufacturer guidelines, Building Registry data and experience stories from the construction processes of pilot building in Tallinn, Akadeemia 5a and in Saue, Kuuma 4 (see Figure 2) were used, which were obtained by interviewing the contractors of these projects. The information from the interviews helped to understand how different factors affect various stages of the construction process. All the collected information provided a more comprehensive understanding of the problems in the field and allowed me to propose specific solutions and suggestions for their improvement.

3 Results

The cases studied showed that in many situations we must deal with the consequences of insufficient investigations and measures, such as unsecured from wet weather joists or the impossibility of lifting elements caused by the presence of eaves of slope roof (see Figure 3).

Figure 3 Temporarily removed roofing material during lifting of the upper elements and lack of temporary scaffolding on the roof area.

In one case, the strength of the plinth substructure (made of tiles) was not verified during the survey beforehand, which led to problems with the installation of the girders. The solution was the addition of a glulam levelling beam and the alternative placement of the steel load-bearing anchors (see Figure 4).

Figure 4 Weak base on plinth (left) and glulam beam installed (right) so that the steel support anchors can be attached lower.

In the second case, the resistance of the soil on the paths of the cranes and hoists was not considered, which led to the replacement of the temporary soil with geotextile and gravel. The resolution of these situations required additional fieldwork (see Figure 5).

Figure 5 Early spring topsoil in the installation area.

The research revealed that an estimated -10°C is the maximum cold temperature at which installation work can be performed. Attempts were made to install girders at a morning temperature of -16°C, but the hydraulic hose of the lift failed to hold up and burst, halting the work. Later the same day, at a temperature of -12°C, there were attempts to install elements, but the crane mast froze. Although the specified crane is designed to operate down to -18°C, a thermal camera showed that due to the wind, the surface temperature of the crane mast was -21.8°C (see Figure 6).

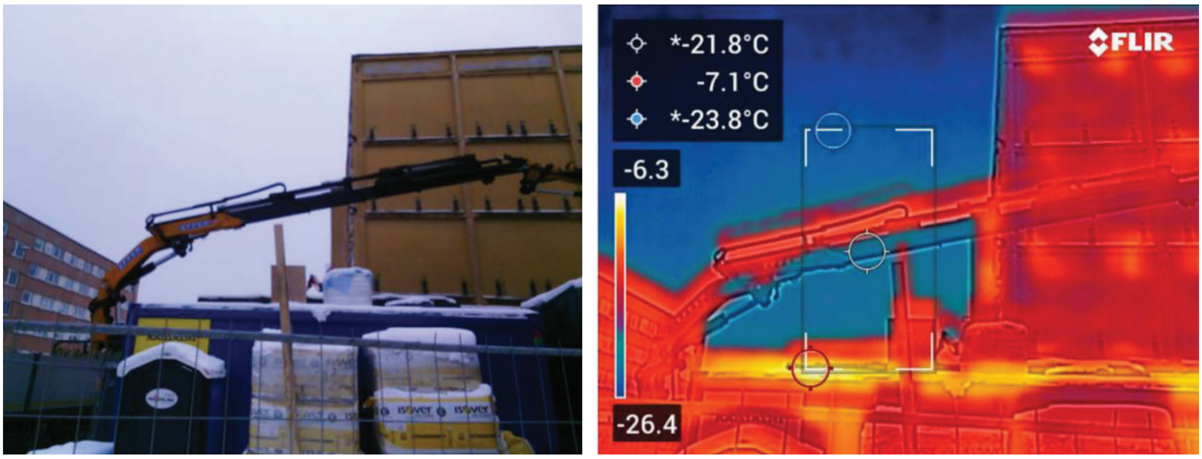

Figure 6 A photo (left) and thermal image (right) of the crane mast showing a surface temperature of -21.8°C.

Problems with elements, such as imperfect buffer layer, nonmatching of elements in the corners of the envelope, and nonconformity of window openings were discussed and measures to be taken agreed upon. The results of inadequate design and working instructions were recorded, such as the installation of girders on uneven surfaces without accurate geodesy measurements, transport and lifting damages, and lack of on-time feedback to designers. Solutions included modification of the anchors for the girder (see Figure 7), for weatherproofing and better packing and lifting, and involvement of the designer to obtain and offer solutions and provide feedback to all partakers involved.

Figure 7 Installation of girder on uneven surfaces before (left) and after (right) repair.

Detailed point cloud processing is also crucial to determine the unevenness of the facade to establish the necessary thickness of the compensation wool layer and the maximum dimensions of the infill (see Figure 8). The aforementioned information is handed over to the design and production teams.

Figure 8 Dimensions of existing windows identified through point cloud processing.

The design team should address all potential actions during the installation of the elements to avoid the need for corrective and reconstruction work on site due to errors, such as the incorrect placement of girders on an uneven surface, damages occurring during the lifting of element bundles (see Figure 9), or insufficient vapour tightness in the lower tie beam area and all sides of the element to prevent moisture from the original wall entering between the structures insulated. Anything left unresolved requires on-the-spot improvisation, and mistakes arising from such ad hoc measures can prove costly.

Figure 9 Damages incurred from lifting with slings.

Recommendations for the design of elements, production, preparation for installation, installation of the elements, and the organization of the follow-up work have been brought together as a checklist to lead in every phase of the process. The list outlines the main activities from the investigation to the completion of the post-installation works. For example, the need for a tightened vapour barrier on the plinth, the sealing of the vapour and air barrier at the eaves and corners, the sealing of the upper element, and the winter installation specifics. The main steps to follow and results to be expected, and compliance to these requirements are meant to be filled in this checklist and controlled by the owner supervisor and by the building site manager. See Figure 10 with an excerpt of the checklist proposed.

	Liik	Asukoht/ala	Tolerants/ vajalik tulemus	Tulemus	Vastavus nõuetele	Märkused
PROJEKTEERIMISETAPP	Kandurid ja tuulesidemed	kandurite kinnitus				
		kandurite kinnitus ebaühtlasel pinnal				
		alumise kanduri tuletõkketööd				
		tuulesidemete kinnitused				
		ülemise elemendi kinnitus				
	Auru- ja õhutõkked	sidepuu ja aurutõkke lahendus				
		auru- ja õhutõkke ühendus horisontaaljätkus				
		auru- ja õhutõkke ühendus vertikaaljätkus				
		ülemise elemendi auru- ja õhutõkke lahendus				
		pooliku torni ajutine katmine				
	Puhvervill	puhvervilla optimaalse paksuse määramine				
	Pakendamine ja transport	pakendamine				
		tõstmine kahveltõstukiga				
		tõstmine troppidega				
	Paigaldusjuhend	projekt täiendatud paigalduseks vajaliku infoga				

Figure 10 Checklist with subtasks to follow in preparation, design, production, installation, and post-installation phases.

4 Discussion

The obtained results indicate that every part of the process can and should be further refined. Preliminary construction research is still underestimated, and subsequent discoveries have proven to be costly and time-consuming. Many project solutions are also still in the experimental stage during the actual construction phase, and thus the final solutions are still under development. During the research, there were situations where a problem was indeed solved correctly, but the feedback given to designers was insufficient for them to implement corrections in future projects. Consequently, comprehensive feedback to designers is pivotal for the success of future endeavours.

Before design work, tests should be conducted on-site under the beams, ascertain the building's settlement issues, and ensure the possibility of accommodating ventilation ducts within the building, considering the potential dimensions of radiators and walls. It is also necessary to measure the moisture content of external walls in different compass directions, and in case of excessive moisture, appropriate measures should be taken. It is also worth checking the load-bearing capacity of various existing structures, such as windowsills, balconies, and canopies.

The elements factories have their quality control systems, and the quality of the entire production process is monitored internally daily. As a result, risks in element production are mitigated, but in addition, on-site supervision of preparatory works and installation is necessary. This can be done effectively if there is a guide from the designers for this purpose. Therefore, it is once again crucial for designers to address all possible solutions to reduce incorrect decisions during construction.

Lastly, it is vital to train the installation teams and subcontractors. During the research, one surprising issue was the absence of a common language between the lift mechanic who works on the lift and the crane operator. There were occasions when the fitter wanted to move a component in one direction, but the crane operator misunderstood and shifted in the other direction. Consequently, proficiency in gestural communication specific to lifting operations is paramount in team training protocols.

The problems identified in this research were addressed, and designers and installers of these projects are aware of them and can take them into account in future projects, but it is also essential to pass this information on to newcomers. Ultimately, a uniform system that can be standardised should emerge. With this, standard solutions and nodes could be developed, which could serve as an excellent guide for future element designers, manufacturers, and installers.

5 Conclusions

In conclusion, the study identifies bottlenecks in the construction process, such as extended processing times in building registers and design-related challenges. It underscores the importance of separating the design from the construction process to avoid potential pitfalls. Additionally, the research emphasizes the need for comprehensive building studies and training for consultants.

Regarding innovation, the study sees potential in standardizing elements using existing materials and further developing certain types of elements. It also proposes novel approaches such as using factory elements for roof renovations, considering the transformation of pitched roofs to flat ones.

The supervision of the process studied showed that it is recommended that more building studies should be carried out and that consultants should be trained. In terms of element standardisation, it is recommended to use and develop already proven solutions which are not yet implemented. The final product should be a solution with essentially no follow-up work needed. In addition, the construction of additional storeys in existing buildings with prefabricated elements could be explored, which may offer financial benefits to housing associations and could help cover part or even all of their own financing.

The results of this work can be applied in the planning, design, and implementation of apartment building renovation projects, aiding both in enhancing energy efficiency and elevating the quality of the living environment.

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Misused timber in renovation

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Abstract

Various problematic timber usage cases are revealed and discussed in order to minimise the repair costs of houses and timber use in places where rapid wood decay can be expected. The photos are based on an external survey of Estonian old residential areas and the author's previous experience of the renovation of old houses. Problematic solutions like double timber cladding, wooden elements in the foundation wall in contact with soil, open-air timber balconies and terraces, new wooden windows and doors with vapour-tight paint and unfinished works are shown in photos and discussed in detail. The purpose of the article is to draw the attention of self-builders to bad practices in order to avoid them in the future. In addition to avoiding temporary solutions, timber should be used in places where optimal durability of the construction solution is guaranteed. This article does not discuss the normal ageing of wood and damage caused by insufficient maintenance.

Keywords: Building physics, Building mistakes, Timber decay, Timber cladding, Exterior paint for timber, Timber terrace, Estonia.

1 Introduction

A study of wooden buildings in Estonia (Klõšeiko, 2011) revealed the main damages and their frequency of occurrence. Builders and owners should learn from these and avoid certain solutions that are not durable. The durability of external timber claddings in Southern Chile based on a total of 102 heritage buildings has been analysed by Silva and Prieto (2021). The study focused on maintenance and building quality was not addressed. Wood is a universal building material, but it cannot withstand a constantly high moisture level and therefore the use of wood in these conditions should be avoided. On the other hand, owners could accept the frequent replacement of wooden parts in moist conditions, but this is not an environmentally sustainable use of wood. The decay prediction model in timber balconies is proposed by Gaspari et al. (2023). There is an available software program, TimberLife Educational Software Program (Forest & Wood Products Australia Ltd, 2013), for estimating timber's service life in different scenarios. There are also many other studies about timber decay in various conditions and climates. In general, in order to increase the service life of timber construction elements, it is important to avoid conditions favourable to wood rot and wood-boring insects. Usually, this is achievable by keeping timber elements as dry as possible.

2 Methods

The results are a side product of an external survey of old milieu valuable residential houses in Estonia. The main aim was to collect statistics on renovation status and examples of damages or renovation mistakes. The findings were documented from the street (photos and filled electronic form). A few examples presented in this paper are from the author's previous practice as an Estonian heritage board advisor. Photos of problematic construction elements were made and the reason for the damage was analysed. The external survey included over 1000 residential houses with an average age of 89 years – building year based on Estonian buildings register (https://livekluster.ehr.ee/ui/ehr/v1; range between 1760 and 2015). Half of the houses were partly or completely renovated or in a few cases renovation work was in progress.

The analysis of this article only includes partly or completely renovated houses where timber in open moist conditions was discovered and where rapid timber decay could be expected or in some cases decay was detected. Due to the low number of detected cases and the expected higher number of hidden similar mistakes, no statistics were made. Many of the presented mistakes can only be visually detected in an ongoing renovation state and, if the renovation is correctly completed, then these mistakes are covered and cannot be detected without physical intervention. The documentation was checked from the buildings registry on three cases where complete renovation was performed (or ongoing). There was no design documentation about these cases. The lack of information about the renovation process can be considered a shortcoming of this study. Houses were documented from the street and the owners were not contacted. If the example was taken from previous practice, then the owner was included in the inspection and more background information is known.

3 Results

3.1 Timber cladding

In several cases, a second layer of cladding was added over the old one (Figure 1). Sometimes a wind barrier was also added in between two cladding layers (Figure 1, middle and right photo). The wind barrier, which has air gaps on both sides, does not fulfil the purpose of the layer. Added layers only improve the visual appearance of the facade, but the same result could be achieved with a smaller amount of new timber and without altering the authentic architectural style of the house. In one case the old boarding was covered with PVC wall cladding (unfinished work). There were houses where double cladding could be suspected but could not be visually checked. Therefore, these cases were not counted.

Figure 1. Second layer of timber cladding can be detected from the corner of the house (left). The second layer of timber cladding with the wind barrier board and distance battens has been added on top of the old cladding, view from the doorway (middle photo). The second layer of timber boarding is added over the old one with two ventilation gaps and wood fibre wind barrier board between them (right).

3.2 Foundation wall

Timber battens are often used to fix foundation wall finishing material (mainly mineral façade panels). The solution is easy to build, but if vertical battens are used which are in contact with damp soil, the battens will rot and the solution has to be replaced after a few years. In Figure 2, the ongoing foundation insulation solution is shown from two sides. Vertical timber battens were placed and then the old stone foundation wall was insulated with sprayed PUR insulation. The timber battens are partly sunk inside the insulation layer and the bottom ends are in contact with either soil or asphalt. In the right photo cement fibre board is installed, which is the underlay of the final finishing of granite tiles. In Figure 3, two unfinished renovation photos with same mistake, but from different houses, are shown. In both cases an expanded polystyrene (EPS) insulation layer is installed between vertical timber battens, which are in contact with soil and will be sunk even deeper into the ground after finishing.

Figure 2. Foundation wall of the same house from two sides. Vertical battens' bottom ends are in contact with soil (left) or with asphalt (right). Finishing layer consists of cement fibre board (right), which was glued over with granite freeform tiles.

Figure 3. Vertical timber frame for the foundation finishing panels between EPS insulation boards on two different houses.

3.3 Wooden balconies and terraces

Open-air (i.e. without a roof) wooden balconies and terraces have a lifespan of between 10 and 20 years depending on the climate conditions and wood treatment and timber species used. During the external survey, one broken balcony was found (Figure 4 left), which was apparently left unfinished during the complete renovation of the house. From previous experience the author has seen completely broken and dangerous terraces on the ground and on top of the roof (second floor level) covered with special terrace boards. For example, in Figure 4 (right) the terrace in the backyard of a wooden apartment building is shown, which has broken boards and a sign that prohibits walking on the terrace. The building time of this terrace is unknown to the author but similar damages have been detected on the terrace of a commercial building with an age of 13 years. Most of the balconies and terraces are located in the backyard and cannot be inspected from the street level.

Figure 4. Unfinished and broken timber balcony of renovated detached house (left). Open-air terrace on the ground with broken terrace boards and sign prohibiting walking on it (right).

3.4 Paint of timber windows

Wooden cladding and windows have lasted longer than 100 years if repainted regularly with suitable paint. However, rot on the lower parts of almost new wooden windows is frequently discovered (Figure 5). The first signs of rot are thin black cracks in the paint. These cracks can appear as soon as two years after the production of windows (Figure 6) and some elements can be completely rotten after 10 years (Figure 5, left). Then the owner has a choice to replace the entire window or to order a replacement for the rotten window parts from a carpenter. This is an unexpected and expensive surprise for the owner. The main reason for rapid damage is too vapour tight and strong paint layer. Therefore, moisture is trapped in the wood and rotting will begin. Sometimes the strong paint is the last strong layer, revealing completely rotten wood after falloff. Other factors speeding up decay include a high indoor air moisture level causing condensation on glass, missing or old window seals and short roof eaves. In comparison, old wooden windows without a protective paint layer (degraded long ago) more than 30 years old have only a darkened surface caused by the sun and the wooden part is still strong.

Figure 5. Lower part of the window frame is rotten due to unsuitable paint. Ten-year-old windows (left) and similar replaced windows with a similar age (right).

Figure 6 Around two-year-old wooden window has the first signs of rot decay: outside view (left) and inner side of outer frame (right).

In Figure 7, the external door of a restored manor house is shown from both sides. The lower part is completely rotten and a finger can be pushed through the door. Although the paint only seems to have minor damage, there is no strong wood below it in some parts anymore. Many windows of the same house had rot damage on the lower parts with similar damage, as shown in Figure 5. These windows were around 20 years old and were repainted 10 years ago with alkyd paint. All windows and doors need to be replaced due to the severe damage.

Figure 7. Lower part of external door of a restored manor house is rotten due to unsuitable paint: internal side (left) and external side (right) of lower part.

3.5 Other timber elements often damaged

Another wide spectrum of wood damage is caused by unfinished works. The wooden elements are not covered by a finishing layer or are periodically getting wet from rainwater. For example, the last metal roofing pane was not installed for more than a year in one case (Figure 8).

 

Figure 8. Two photos of different edges of the same house with unfinished roof installation and uncovered timber elements. The roof work has been waiting for completion for more than a year, as a green layer of algae has already formed on the metal sheets.

In several cases, instead of the standard gable trim of the metal roof, a wooden edge board was installed, which was damaged together with soffit boarding (Figure 9). Similar placement of timber rake boards is widely used with cement fibre roofing, which needs periodical repair. It can be considered an old building practice of self-builders which is not following the installation instructions of specific roof products. For example, special metal gable trim elements are produced and installed on metal roofs such as in Figure 9, with the same lifespan with roof cover. In many cases the gable trim elements were not installed after roof replacement and rot damage of the underlying timber batten ends was detected.

 

Figure 9. Wooden rake board of the new metal roof is decayed and the soffit boards also have rot damage (left). The end view of the roof shown in the photo on the left, where parts of rake board are missing (right).

4 Discussion

The step-by-step or complete renovation of detached houses in Estonia is often performed without detailed project documentation. Therefore, it can be concluded that the solutions presented in this paper were built by self-builders or by building workers based on their knowledge. The owners themselves are also often not competent to assess the quality of the ordered construction works, and construction supervision is not included in simpler works. Therefore, it is important to spread knowledge about best practices and also show common building mistakes. If building errors causing wood rot are avoided, the need for timber decreases and repair costs during the service life of the building will also decrease.

From a heritage-preserving point of view, it is not bad practice to preserve old valuable wooden boarding below the new layer if there is no knowledge or the willingness to restore old boarding using the correct recognised methods. Then the new layer can later be removed and a valuable finishing layer can be correctly restored and exposed together with all other valuable details. The conservation of old decayed finishing layers under new layers is often easily reversible and in the heritage protection community it is the preferred solution compared to complete replacement of the old layer with a new one. Definitely the best practice from both a heritage-protection and environmentally friendly point of view would be to restore the old cladding and only replace the unusable elements with copies. When combining the restoring of the cladding with improving the thermal performance of the external walls, then the old boarding has to be numbered, carefully removed and, after insulation works, restored and reinstalled again. In this case, the project documentation must contain detailed section drawings, which take into account the changes in the proportions of the structures.

In Estonia, it is common to insulate the foundation wall as one of the first energy-renovation measures. The aim of the owners is to increase the temperature of the first floor. Insulating the foundation wall is cheaper compared to insulation of all the first floors, but its influence on energy performance improvement is minor (close to zero) in the case of detached houses without a heated basement floor. By comparison, the decrease of delivered energy consumption is 11-12% after adding 300 mm insulation below the first floor (Alev *et al.*, 2014). The goal of warm floors is of course achieved by insulating the floor, although a small increase in floor temperature can also be achieved by insulating the foundation. However, the owners of old wooden floors run into the risk of developing dry rot when insulating the foundation and existing ventilation openings are closed during the insulation process (Pilt, 2022). It should be common knowledge to building workers that wood in contact with soil, groundwater or road surface will rot quickly. Builders have performed fast and easy foundation wall insulation and finishing solution without considering its durability. There has probably been no construction supervision in the detected cases. On an old damp foundation wall (common situation) timber elements should be avoided completely and galvanised metal furring suitable for damp conditions should be used if needed. With old houses, traditional thick plaster finishing of the foundation walls is preferred in order to preserve the external appearance of these houses in milieu valuable areas.

Adding an open air wooden terrace near the house seems to be a trend of increasing popularity during the last decade. In the humid Estonian climate the durability of such a terrace without a roof is between 10 and 20 years depending on the materials used and the surrounding conditions (presence of trees, dampness of soil, influence of sun and wind etc.). After this it becomes dangerous and needs demolishing or replacement. Old detached houses have closed verandas with large windows or small balconies on the second floor level. In old houses wooden floors always are in roofed parts and uncovered terraces are always stone paved. Therefore, it is advisable to rely on historical experience and pave uncovered areas with stones, avoiding wasting timber on temporary solutions.

The use of the correct paint on the external surfaces of old wooden buildings is a wider topic. In this paper, the rapid decay of rather new windows and doors was in focus. Although the timber quality used in the production of windows and doors has been low during the last few decades compared to timber used in older windows, the main reason for decay tends to be the wrong choice of paint. Traditionally, windows and also facades were painted with linseed oil paint in Estonia. If the worn paint has been periodically repainted with the same traditional paint, then these timber elements have lasted over 100 years. If new wooden windows are finished with modern paint (alkyd paint) and need replacement after 10 to 20 years, then the modern practice should be reconsidered taking into account the durability of older traditional solutions.

5 Conclusions

It is important to draw the attention of houseowners and building workers to building mistakes made by others. Learning of these mistakes and improving building practice helps to reduce repair cost during the service life of the building and reduce the timber needed for repairing. Improper use of timber is the result of the lack of knowledge of self-builders, influence of architectural trends and the use of untested finishing materials advertised as strong and durable. Covering the old wooden cladding with a new one is easier and faster to build, but considering the optimal use of resources, it is assessed as a misuse of timber.

It should be more frequently reminded to the building workers and owners that wood in contact with damp soil, water or road surface starts to decay rapidly. Therefore, using timber elements in such conditions must be avoided. Another reminder to owners should be to always complete building works, because half-finished solutions are not durable and will degrade, leading to the need for major repairs later on.

If overly vapour-tight modern paint together with other factors causes new windows and doors to rot rapidly, then changing the paint type may be the solution to increase their durability. The durability of stone pavement on open areas without a roof is considerably longer compared to wooden terraces. Therefore, the owner should be made aware of the short durability of their trend-driven desire and be advised to avoid it.

6 Acknowledgements

This study was supported by the European Commission through the LIFE IP project BuildEST (Reference: LIFE20 IPC/EE/000010).

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FORUM WOOD BUILDING BALTIC

REGENERATIVE AND CIRCULAR ARCHITECTURE

3cycle. An open source circular modular construction system
Renee Puusepp

Prolonged carbon storage and CO2 reduction by circular design with wood
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3cycle. An open source circular modular construction system

Renee Puusepp, PhD[1]

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Summary

The 3cycle project introduces an open-source, modular construction system designed for circularity and sustainability. Utilizing biogenic materials, the system's methods include modularity for reusability and adaptability. The pilot application on the Elektrilevi building demonstrates practical feasibility, showcasing a reconfigurable wooden educational structure. Results indicate a significant reduction in environmental impact, while conclusions affirm the system's potential to transform construction practices in line with circular economy principles.

Key words: Circular construction, modular architecture, design for manufacturing, assembly and disassembly

1. Background

The 3cycle project emerges from comprehensive research at the Estonian Academy of Arts, aiming to address the environmental impact of construction with a novel, open-source modular system. This work is situated in the context of the global need for sustainable building practices that can contribute to a reduction in carbon emissions. The development of the 3cycle system is an academic response to this challenge, employing modular design and biogenic materials to facilitate the easy assembly and disassembly of structures. A key aspect of the research was the application of the system to a real-world context, demonstrated through the Elektrilevi building project. This case study serves to evaluate the practicality of the system's principles, focusing on the lifecycle and adaptability of the modular components, and the feasibility of integrating such a system within current construction practices. The project aims to offer insights into the scalability of circular construction methods and their potential for widespread adoption in the industry.

2. Methods

The 3cycle project's methodological approach was characterized by a continuous development cycle, integrating design, manufacture, and assembly disciplines. Employing an integrated design process, the team collaborated across specialties to refine the modular system. This iterative process involved designing, building, and then re-incorporating the findings back into the system to enhance functionality and sustainability. Prototyping was crucial, with each iteration tested in real-world conditions through projects like the Elektrilevi building. This hands-on approach not only ensured the system's practical viability but also fostered a feedback loop that propelled further innovations within the 3cycle system. The methodology thus underpinned a dynamic development environment, with each phase informing the next, ensuring that the system evolved to meet the changing demands of sustainable construction practices.

3. Results

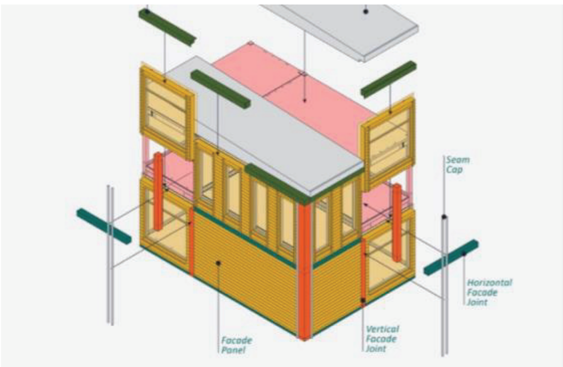
The results of the 3cycle system development are largely still yet to be seen. The Elektrilevi building served as a successful pilot, illustrating the practicality of the modular approach. Throughout the project lifecycle from design to assembly, the research and development team gained substantial knowledge for improving the system in terms of cost, circularity and ease of assembly. Additionally, the adaptability of the design was evidenced by its capacity for reconfiguration and expansion. These outcomes not only validated the system's foundational principles but also highlighted its scalability and effectiveness in real-world application, marking a positive step towards environmentally conscious building practices.

4. Conclusions

The 3cycle system's research journey reveals a promising direction for sustainable construction, balancing innovation with practicality. The Elektrilevi case study not only serves as a proof of concept but also as a catalyst for ongoing enhancements. The knowledge gained from this hands-on application has been instrumental in refining the system's cost-efficiency, ecological footprint, and assembly processes. In conclusion, 3cycle stands as a testament to the potential for modular and circular construction methods to evolve and adapt, providing a scalable and environmentally responsive solution for the construction industry's future.

5. Acknowledgements

We would like to thank the following partners involved in the research and in the construction of the pilot building: Estnor, Elektrilevi, NOMAD architects, WHAT IF, Kaltech, iBET



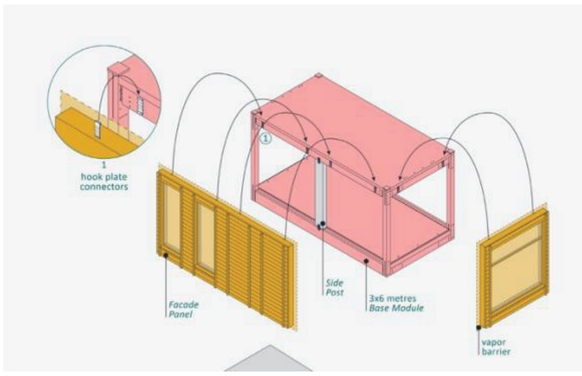


Figure 1 and 2 – Extracts for 3cycle system guide available on https://patternbuildings.com/downloads/

Prolonged carbon storage and CO_2 reduction by circular design with wood

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Summary

The benefits of circularity and biogenic carbon storage are often overlooked. This study links circular design of buildings and prolonged biogenic carbon storage. Circularity in architectural design can extend the service life of a building frame, whilst forests grow back and store more carbon. Static and dynamic Life Cycle Assessment has been carried out, modelling and quantifying potential whole life carbon benefits as a holistic system. Through this circular design approach, the effective implementation of built-in flexibility and adaptability can extend the service life of a building, unlocking the environmental benefits of biogenic carbon storage of wood products in buildings.

Key words: adaptable building, biogenic carbon storage, carbon sequestration, circularity, embodied carbon, flexible design, wood products

1. Introduction

It is well established that timber construction is one of the most effective strategies to decarbonize construction. It has become one of the main arguments for property developers to shift towards building with wood, especially those who have carbon reduction as one of their key strategic goals. Using timber-based products sourced from sustainably managed forests has many environmental benefits. The interactions between sustainably managed forests and timber products play a relevant role in carbon sequestration. Additionally, biobased products are unique when considering their biogenic carbon storage.

Stora Enso, along with other industry partners, has developed a concept building to demonstrate how it is possible to design for mixed-use, flexible, and adaptable structures that allow for future building use changes and repurposing.

1.1. Purpose

This study aims to understand and quantify how the use of timber for the structure of a building can reduce carbon emissions in comparison to conventional and widely used materials. To assess the real effect to the Global Warming Potential (GWP), a needed understanding is the relationship between the carbon stored in the building and the carbon sequestration of sustainably managed forests, in which harvested trees are re-planted to maintain their biodiversity, productivity, regeneration capacity and vitality. Therefore, this article explores and quantifies the potential climate mitigation effect of using flexible and adaptable architecture to extend the service life of buildings, in relation to sustainable forest growth as a holistic system.

2. Methods

The study is based on the mixed-use building concept by Stora Enso. The timber-based concept building and it´s benchmark are assessed according to the Method for the Whole Life Carbon Assessment of Buildings (the 2021 edition) issued by Finland's Ministry of the Environment. In addition to the application of standardized static Life Cycle Assessment (LCA) methodologies, a dynamic LCA (DLCA) approach is applied to understand the effect of timing on both building and on forest regrowth level.

3. Results and discussion

The reduction of the Whole Life Carbon (embodied and operational emissions) is 11% from the mixed-use timer building concept against the concrete benchmark building, considering a RSL (Reference Service Life) of 50 years and applying traditional LCA. To better understand the impact of carbon storage and carbon sequestration in regrowing forests, variations of the RSL and LCA approach are applied. DLCA demonstrates the benefit of using timber and the effect of biogenic carbon storage in the material on both RSL of 50 and 80 years. Assuming that carbon equivalent to that stored in the installed timber elements will be captured by growing trees in sustainably managed forests after construction within the RSL of 50 years, the whole life carbon could be reduced by 74% to 2,84 kg CO_2-eq./m² floor area/year. By applying circular design methods and assuming basic refurbishment after 50 years, which is allowed due to the flexible and adaptable building design to increase the RSL to 80 years to align with a longer tree growth time, the whole life carbon results in -0,09 kg CO_2-eq./m² floor area/year.

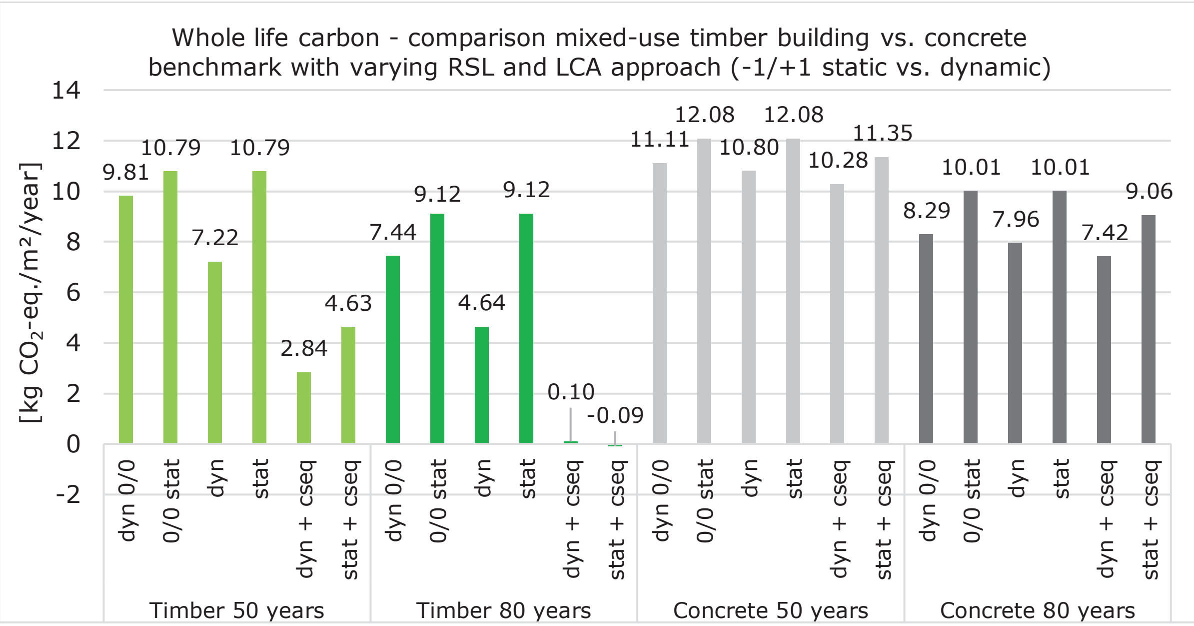

Figure 1. Comparison of the whole carbon between mixed-use timber building concepts and concrete benchmark buildings. (dyn = dynamic; stat = static; cseq = carbon sequestration)

4. Conclusions

This study makes evident that the current LCA methods are overlooking some of the major benefits of building with timber and its linkage to sustainable forestry. Carbon reduction potential by using timber shows clear advantages compared to conventional concrete buildings. This carbon reduction benefits can be significantly increased by implementing circular design, extending service life for the wood products and accompanying carbon sequestration. The real benefit becomes evident when linked to forest regrowth and development of dynamic LCA models. The authors see an opportunity and exercise to further develop standardized methods to account for these effects in LCA calculations.

5. Acknowledgements

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Prefab light clay-timber elements for net zero whole-life carbon buildings

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Abstract

"Net zero whole life carbon" is an ambitious climate target that refers to neutralizing and offsetting the entire LCA-based carbon footprint of a building, including both operational and embodied greenhouse gas emissions. Especially in the Northern climate, viable building envelope structures must, therefore, provide good thermal insulation and low embodied emissions. Carbon offset is typically based on excess on-site renewable energy or purchased carbon offsets disconnected from the building and the site. Viable strategies for carbon neutrality start by minimizing material-related and energy-related CO_2e emissions. As a result, new kinds of building envelope structures have been recently introduced in the academic literature and experimental building projects.

Traditional construction materials, such as timber and clay, have been sourced locally and processed manually, providing good results for the embodied emissions in life cycle assessment. Recent studies on clay-based construction materials have concluded that more research on clay as a construction material is needed, in particular considering its environmental performance.

One specific concern in the Northern climate is that the weather conditions limit clay construction outdoors and prevent industrial-scale application of these solutions. The methods of prefabrication can address these issues.

In this study, we introduce the critical technical and environmental properties of a new prefabricated wall element based on a combination of light timber frame and light clay. In a hybrid light clay-timber structure, a mixture of clay and hemp shives is cast between the timber studs. On the one hand, the novelty of this wall structure is the prefabrication that enables industrial applications and upscaling without the limitations of weather conditions. On the other hand, the study shows superb environmental performance considering multiple aspects related to global warming: embodied emissions, thermal insulation, and the benefits outside the system boundary (carbon handprint) reported in the D-module of the LCA framework.

The study also shows that natural materials require a different approach than synthetic materials, for which the production processes typically aim at consistent quality to ensure specific material properties and the desired performance in building use. There may be variations in the properties of hemp and clay, especially when local sourcing is prioritized for better environmental performance. Moreover, the mixing and installation process have a significant impact on the final properties and the performance. We show that constructing a light clay wall is a knowledge-intensive process that may result in very different technical properties.

We argue that the case study demonstrates a paradigm shift in developing building envelope solutions. The future low-carbon building solutions are knowledge-intensive but prioritize local, natural materials and minimize the processing of these materials. The quality control could be based on the grading of natural raw materials, similarly to the grading of sawn timber.

In light of the results, we discuss the interpretation of the net zero targets and the viability of accounting for the benefits beyond the system boundary, reported in the LCA framework as module D impacts (also referred to as "carbon handprint") as a carbon offset.
The best specimen of prefabricated light clay-timber elements outperforms all light timber frame solutions with alternative insulation materials in carbon footprint and provides a superb carbon handprint.

Keywords: Clay structure, timber structure, carbon footprint, carbon handprint, prefabrication

Fig. 1. Prefabrication of light clay-timber exterior wall elements (Photo: Juha Päätalo).
Fig. 2. Installation of prefabricated light clay-timber wall elements (Photo: Juha Päätalo).

Fabrication reconsidered: Root chair; robotic milling technology

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Abstract

The aim of this paper is an exploration of the development of digital tools in architectural design practice in the context of woodworking. The study presents the utilisation of robotic milling fabrication, its benefits and limitations, focusing on residual tree stump. The process involves 3D scanning technologies, the optimisation of the geometry using a variety of digital tools, and the application of artificial intelligence. The project offers a new aesthetic insight into the symbiosis between robot-generated processes and nature-generated processes. The study concludes with a critical evaluation of the potential for the use of robotic and computational technology in architectural design practice. It respectfully reflects on the possible transformation of traditional woodworking craftsmanship to meet the digital and technological demands of the 21st century.

Key words: Robotic milling, Artificial Intelligence, digital optimization, 3D Scanning, Residual wood

1. Introduction

1.1. Background

With the emergence of digital tools in architectural design, there is a corresponding rise in digital tools for fabrication and materialisation, requiring architects to adopt an active and responsible approach in this process. New developments in digital design and fabrication have the potential to create both positive outcomes, such as sustainable practices, optimization of materials and resources, novel architectures, and innovative aesthetics; and negative outcomes, such as unsustainable growth and environmental degradation. Additionally, there may be unforeseen consequences resulting from these developments. Therefore, it is crucial to conduct a critical assessment that takes into account not only technological implications but also environmental and social factors.

The project was undertaken as part of a client agreement with the Academy of Arts, Architecture and Design in Prague, under the direction of Imro Vasko and Shota Tsikolyia of Studio Architecture 3. The aim was to design, develop and produce a furniture object for the ITB showroom in Bratislava. The Slovak architectural studio Šebo-Lichý commissioned the work. The object is meant to be a prototype that represents a given manufacturing technology focused on form flexibility and an environmentally sensitive approach to the chosen material.

1.2. Motivation

Wood is a distinctive material that warrants further consideration due to its multifaceted ecological advantages. As it is renewable, reusable, and recyclable, this item has the additional benefit of absorbing carbon dioxide. The project specifically focuses on residual wood, namely, a tree stump - a component of a tree that is frequently neglected and not commonly utilised in standard fabrication processes. The tree stump is often an overlooked and unused part of the tree, making it an ideal material to work with. Our decision to use it aims to establish a new purpose while tackling the reduction of production waste, which is vital for ecological sustainability.

We were interested in analysing a wooden object that contains areas of decay and debris as well as various structural flaws. The root base of each tree is unique and displays a captivatingly complex form. Our objectives were to devise a digital production method for residual wood, employ contemporary technologies to create a design, retain as much of its innate traits as practicable, fabricate and showcase the end product.

2. Methods

2.1. Residual wood: identification process

The first step was to identify appropriate wood for our intended use. The criteria we have prioritised are that the wood is a residual wood obtained from local forests, fields, or compost heaps; the wood has no other intended use and is left to decompose. We selected several specific tree stumps based on their ideal characteristics for us: the upper part of the trunk was large enough to be utilised, it possessed a sufficiently suitable shape for prospective chair production, and it was as dry and healthy as possible. One of the most prominent challenges we encountered involved the natural state of the stumps. Frequently, the tree root was still buried beneath the ground which led to heightened humidity levels, a significant risk of wood-dwelling organisms, and potential issues with cracking during future processing.

Figure 1 found residual tree stump

2.2. 3D scanning

After collecting a number of stumps with potential use, we began the process of 3D scanning. We initially utilised the mobile application Polycam, which allows objects to be scanned using IPhone LiDAR. We found the app to be remarkably user-friendly and well-suited to our need for converting the wood's geometry into a digital format. Several 3D models of specific roots were generated and were ready for further processing in Blender, Rhinoceros 3D and Grasshopper 3D softwares.

As a primary consideration in our wooden chair design was its weight and massiveness, we began to look at ways of effectively and systematically subtracting the mass of the wood to make the chair relatively light. We identified the approximate seating area and produced numerous iterations of the chair's design.

Figure 2 3D scan of the tree stump

2.3. Geometry optimization

A Grasshopper 3D Topos script for topological optimization was established. We were able to select the appropriate weights and eliminate the chair's seating area using this tool. The majority of the upper planes were utilised to generate approximately 100 distinct configurations and iterations. After reviewing each outcome, we deliberated on the best geometry for our project. A few of the results allowed for the chair to be milled from the bottom part as well. The proposed solution resulted in significant weight loss; however, its implementation presented several difficulties when configuring our tool to accommodate it. As a result, we were obliged to strike a balance between a completely hollow and thin structure and the massiveness of the tree stump.

Using a generated parametric marching cube pattern in our Grasshopper Topos script, we successfully simplified the chair's geometry and observed its side areas. By altering the size of the marching cubes, we could adjust the level of detail with precision. The Grasshopper 3D and Rhinoceros 3D processing was followed by the smoothening of the chair's seating parts, resulting in the creation of the most suitable and harmonious geometry. All the smoothening adjustments and mesh errors were rectified in Blender. To enhance the design of seating and side surfaces, and ensure they are better suited to the human body, we decided to replace the external smoothness with AI-generated textures. The simplification of the geometry by using Grasshopper 3D topos script with marching cubes offered us the look of the side areas of the chair. We could have set the size of the marching cubes which would determine the detail. After the Grasshopper Rhinoceros process we have smoothened the seating parts of the best suitable and harmonic geometry in Blender and adjusted all of the errors in the mesh. In order to design seating and side surfaces way more interesting and adjusting to the human body we decided to displace an external smoothness with AI generated textures.

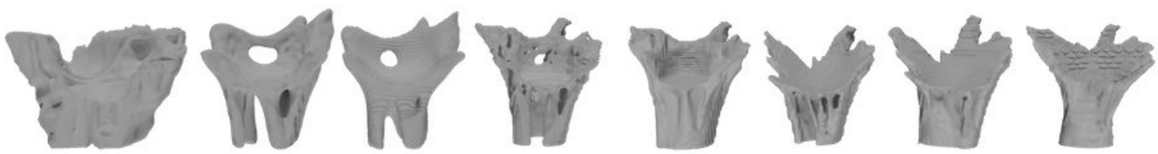

Figure 3 process of developing final design using geometry optimization

Figure 4 comparison of subtracted wood mass

2.4. Artificial intelligence

The use of Artificial Intelligence in architectural practice resulted from our prior semester investigation into its application. As architects, we opted to adapt to rapidly developing digital design tools while incorporating them into our design process thoughtfully. Our objective was to develop a chair with a distinctive and comfortable seat, which Artificial Intelligence provided the means to achieve. By utilising Artificial Intelligence capabilities, we have produced a visual archive of textures that has been formulated through our AI-trained imagery of the muscles located in the seated region of the human anatomy.

During the process, we tested AI learning and created our libraries of learned data. For the processing, we primarily utilised the Stable Diffusion interface on Google Collab. We also used Google Collab for AI learning. During the process, we tested AI learning and created our libraries of learned data. For the processing, we primarily utilised the Stable Diffusion interface on Google Collab. We also used Google Collab for AI learning. The AI training process followed this structure: Firstly, we uploaded images of renowned experimental chairs, such as those created by Gilles Retsin and Manuel Jiménez Garcia. Subsequently, we proceeded to train the AI model. Trained images are limited to only one prompt, but this process can be repeated endlessly, allowing for multiple prompts within one AI model. We acquired images of experimental chairs and simple linear textures and combined the two to create the first prompt of chairs with added textures. This resulted in a remarkably successful outcome, displaying a wooden chair with wavy patterns. However, this method was not utilised in our final design. Instead, we have successfully produced a 2D seamless texture and applied it to the seating geometry using Blender displacement. The AI learning process utilised cut vector sketches of the back and buttocks, resulting in multiple satisfactory outcomes. We applied varying textures to different areas of the seating for added interest. This process produced a range of 3D prototypes which were subsequently tested for geometry by printing on a smaller scale using a Prusa 3D printer. The results were evaluated before moving on to the next phase.

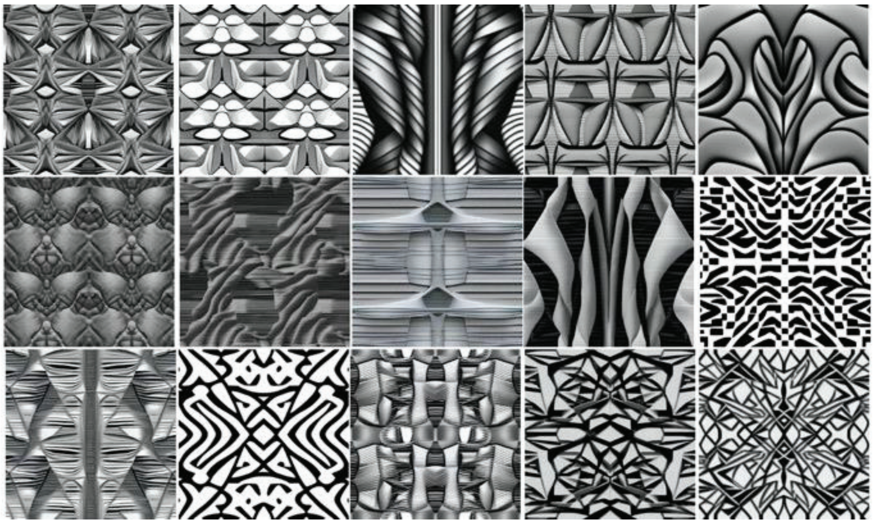

Figure 5 Ai generated seamless patterns

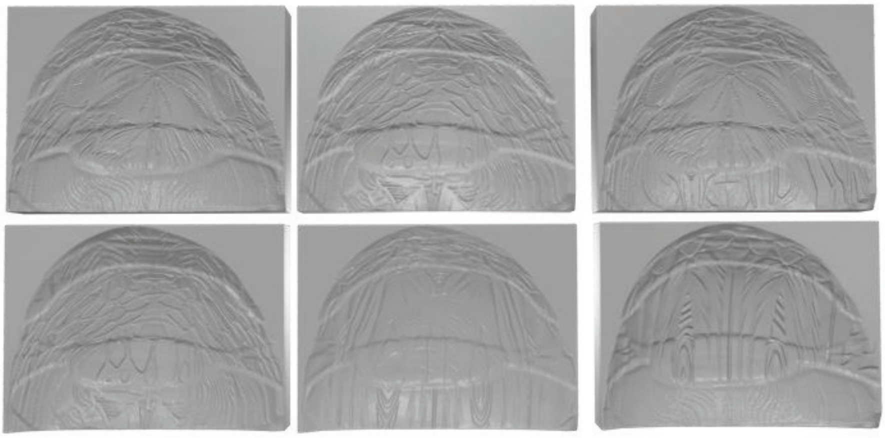

Figure 6 displaced Ai generated textures on seating prototype

Figure 7 final 3D model

2.5. Robotic milling

The initial and most significant challenge we encountered was the price of robotic milling. Initially, we assumed the milling process would be a straightforward task; locate a stump, design a chair, and start milling. However, the process was more complicated than anticipated as we had to manually remove some wood mass to reduce the milling time and cost of production. We also discovered the limitations of reality in turning a vision into a real object. Nevertheless, it proved to be a pleasant experience to merge traditional woodworking skills with modern technological advancements. Using robotic milling technologies offers significant benefits to our project due to the precision and detail they can provide compared to manual methods. This highlights the importance of adopting this technology for our project's success. The entire robotic milling process is divided into three phases: preparation, robotic milling, post processing.

2.5.1 Preparation

Before proceeding with a 3D milling of the tree stump, we carried out tests on various prototypes using the CNC mill available at our university. We made a prototype of a block by glueing three oak planks together, and the resulting block was compatible with the CNC machine we had available. We carried out tests on a section of the seating area and on the adjacent side area, both with dimensions reflecting actual size. The results of the test milling were highly detailed; however, small angle errors were visible due to the CNC mill's limited ability to mill from only one angle. These test objects were instrumental in enhancing our comprehension of the material's behaviour and the attributes of our design.

During the final phase of crafting the root chair, we contacted more than five factories in the Czech Republic that possess 3D milling capabilities using robotic arms. A requisite condition was to have a rotational table that suited the chair’s dimensions; if not, we would have been unable to mill the chair from all angles. If we had failed to procure the appropriate equipment, our only recourse would have been to divide the chair into two pieces for individual milling and reassembly. This process could have been challenging due to potential wood distortion as it dries. However, we were able to find a Workshop of 3D Technologies at the Faculty of Fine Arts, University of Technology in Brno, that had a robotic setup with a rotating table, effectively resolving the problem. The Workshop of 3D Technologies is led by doc. Mgr. Tomáš Medek and his assistant Mga. Dušan Váňa Ph.D. Thanks to their expertise in wood milling, we gained valuable insight into the process of preparing data and materials for 3D milling. Their knowledge proved to be immensely helpful.

During our initial meeting, we concluded that milling the entire stump in its current state would not be practical. Additionally, there was uncertainty regarding the material, as there may have been some remaining dirt inside. Furthermore, their woodworking facility had not previously worked with such a durable wood like oak, as they typically use linden wood planks. Just extracting a large amount of wood mass was not an appropriate process due to the rapid increase in price of robotic milling. Therefore, we opted to manually remove the wood using traditional sculptural techniques. Our primary focus was to eliminate the wood mass surrounding the seating area, followed by the back of the chair. We also adjusted the standing surface of the stump by first cutting it with a chainsaw, followed by smoothing it with finer tools. After approximately three days of manual labour, we prepared the stump for milling. We affixed the stump onto a rectangular plank to enhance its measurability in a digital space. We rescanned the model, this time including the plank, to obtain a comprehensive 3D model.

After the wood was transferred to Brno, the workshop assistant began preparing data for the robotic arm. One complication arose when our 3D scan of the real wood did not align with the 3D model. The assistant had to rescan the model with a kinect scanner and scale it to fit properly. In suitable software for the robot, the object surfaces were partitioned into separate sections according to the angle of reach of the robotic arm without necessitating rotation of the table. From there, paths were generated for the milling tool on the selected parts.

2.5.2 Robotic milling

The object is milled in two parts (layers): the seat portion is finely and smoothly milled while the non-seated side portions are roughened, resulting in an intriguing texture along the robot's path. The areas had a slight height difference of about 3-5 millimetres, making the milling areas visible if you focus on them. The oak stump we harvested posed a challenge during milling due to its rigidity. However, the milling process was ultimately manageable. Our backup plan was to use fruit wood, which offered an intriguing knobby texture and abundance of branches in case the oak proved too difficult to work with. One issue encountered in the milling process was when the drill bit improperly removed wood during the roughening stage, leaving behind a small mess as non-detached wood shavings. This issue was isolated to specific robotic arm rotations.

The initial layer of the milling process used a 40 mm drill bit for roughening. Then, we performed more detailed milling on the seating part using a 5 mm drill bit. We decided to reduce milling time and expenses by leaving the side areas rough rather than milling them to full seating detail. This led to impressive flat surfaces that highlighted the visible pathways of the tool. The design details on the seating area were prominently visible with a finely milled surface and excellently executed pattern. This is a significant upgrade from our previous CNC pattern milling prototype that could only mill from a single angle.

2.5.3 Post processing

After a total of three weeks the milling of the root chair was completed. The working time of the robot alone took about three days to complete. After the chair was transported back to Prague, the final aesthetic and functional adjustments were made. The chair was manually cleaned to remove the final imperfect remains of the milling process. The wood was coated with a protective layer of carnauba wax and then polished using a polishing wheel. This wax emulsion serves as a safeguard against water and further staining of the wood surface, as well as preserving its natural appearance, increasing its durability and resistance. Finally, felt pads were attached to the lower standing surface to give the chair better stability and quality.

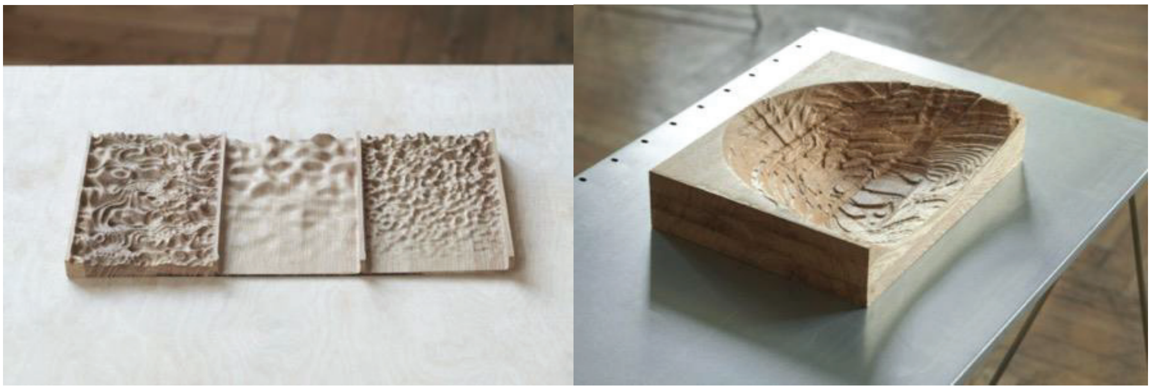

Figure 8 preparation:test prototypes

Figure 9 preparation: manual woodworking

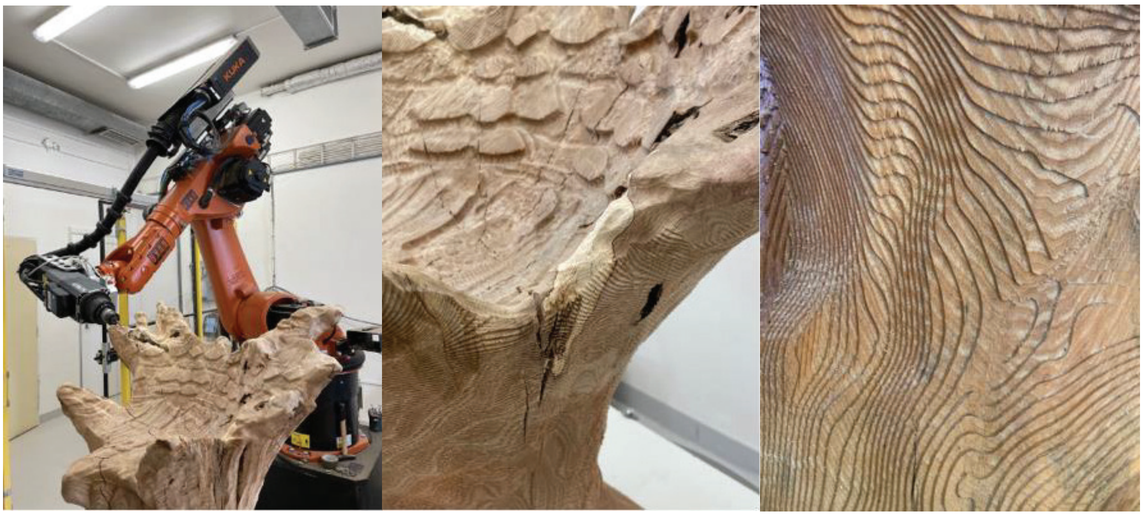

Figure 10 robotic milling

3. Results

The project aimed to explore a responsible approach to the latest advances in digital design and fabrication tools, while prioritising sustainable practices. The process resulted in the identification of the included findings:

3D robotic milling exhibits significant potential for future manufacturing processes due to its geometric capabilities, high-detail capacity, excellent quality of results, adaptability, speed and automation; There is potential in utilising residual tree stumps and transforming them into both functional and aesthetically pleasing elements, thereby giving them a second life; Working with wet wood can cause problems, so it is best to use dry wood whenever possible. However, finding a tree stump without any defects is problematic, so we prefer to adapt our expectations to the natural shape of the wood and operate in harmony with its condition; Due to cost considerations, it was necessary to find a compromise between the proportion of human labour and the proportion of robot labour; 3D robotic milling technology is not yet widely accessible; The overall expense incurred by the robot's operation amounted to approximately 45,000 Czech crowns; The entire process lacked automation and needed ongoing modifications between the actual object, 3D scan, and 3D model, which were all within multiple software programs simultaneously; The unique geometry of each tree stump makes fabrication challenging to translate into large-scale production that can compete with conventional manufacturers of wooden furniture in terms of speed and quantity. There is no chance of using a mould in this case. Instead, a unique workflow is required for each individual tree stump.

Figure 11 final root chair

4. Discussion

During the project's research phase, we explored potential technologies that could have benefitted the process. Of particular note is the use of ultrasonic scanning technology. This method can identify decayed areas in wood by measuring the speed of sound propagation in the material. Healthy wood exhibits a higher speed of sound propagation compared to rotten wood. As rotten wood has a lower density, the speed of sound is lower. An ultrasonic scanner can detect moisture in wood, which may indicate the presence of rot. If we have the opportunity to use this technology, we could improve the quality of the final product by ensuring the wood is in almost perfect condition after the purge process. Additionally, there are various options for removing rot that could be applied to our project: Chemical removal: involves using substances like pyroxylin and epoxy resin to eliminate rot from wood; Thermal removal: involves burning to remove rot from wood; Vacuum removal: the rot can also be removed through vacuum methods, such as vacuum impregnation. The process can be automated using a robotic arm equipped with a range of tools, including routers, knives, and more. The robot arm can be programmed to accurately and efficiently remove rot, minimising material loss and providing precise results. Furthermore, a vacuum device can be attached to the robot arm to eliminate debris and dirt, thus fostering a more hygienic and secure work environment.

Another potential method to enhance our fabrication process would be through automation of the programming and scripting stage. If it were possible to create a tool that allowed us to send a 3D scan of the tree stump, which could then be automatically modified to meet our specifications and sent to the robot for milling, it would significantly accelerate the entire process.

A future topic for discussion revolves around the emergence of new aesthetics resulting from robotic manufacturing technologies. The possible role of artificial intelligence in this remains questionable.

Further evaluations will be required once the chair has been in use for a certain period of time. Its intended placement in the public showroom area and subsequent interaction with people will reveal numerous strengths and weaknesses of the Root chair, providing an opportunity for further learning.

5. Conclusions

The project's development centres around the integration of technology and nature. The goal is to establish a harmonious collaboration between natural processes, including wood structures and its imperfections, and computational processes such as robotic fabrication and artificial intelligence. This synergy is crucial to fully harnessing their benefits. This process has taught us to be humble about traditional woodworking craftsmanship. We aim to regard this craft with respect and envision its transformation in the 21st century by implementing digital and robotic technologies. We understand the importance of revitalising decaying wood, discovering environmentally friendly ways of using residual wood and reusing it for meaningful purposes. Our critical examination of digital fabrication seeks to identify meaningful solutions and responsible actions for the advancement of technology, the environment, and society.

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Mga. Dušan Váňa Ph.D – assistant in Workshop of 3D technologies (Faculty of Fine Arts of Brno University of Technology)

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FORUM
WOOD
BUILDING
BALTIC

LIFE-CYCLE-COSTING IN WOOD CONSTRUCTION

Modelling the decay risk of exterior wood from detailed 3D geometries
Jonas Niklewski, Richard Acquah, Philip Bester van Niekerk, eyyed Hasan Hosseini, Anna Sandak, Jakub Sandak

Bioinspired living coating system for regenerative and circular architecture
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Villu Kukk, Jürgen Hiiekivi, Targo Kalamees

Modelling the decay risk of exterior wood from detailed 3D geometries

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Summary

This study demonstrates a procedure for calculating the risk of fungal decay in building envelopes from detailed three-dimensional geometries. The method integrates simplified climate analysis, moisture content prediction by data-driven modelling, decay modelling and dynamic factorization to account for distance to ground and contact faces. The analysis gives the fungal dose over individual elements, which is proportional to the time until the onset of decay. The work aims to contribute to user-friendly and open-source tools which facilitate performance-based service life assessment of wood.

Key words: Wood, Fungal decay, Building envelope, Service life, Modelling

1. Introduction

The durability of wood depends on a variety of biotic and abiotic factors. One of the main concerns in the design of exterior applications is material deterioration stemming from fungal decay. Since the process of deterioration requires free water, fungal decay is mainly relevant for applications exposed to water. For building envelopes, wind-driven rain is the primary source of water.

This study demonstrates a detailed yet relatively simple procedure for calculating the risk of fungal decay in building envelopes. Starting from a three-dimensional geometry, we demonstrate how the risk of fungal decay can be estimated using climate analysis, moisture content prediction, decay modelling and factorization. The study extends the previous work by Niklewski et al. [1], by integrating the data-driven model from Hosseini et al. [2] and developing a procedure for detection and labelling of contact faces.

2. Methods

The risk of fungal decay is quantified in terms of dose accumulated over a reference year, according to: $D = D_0\, k_1\, k_2$, where D is the annual dose, D_0 is the annual reference dose and k_1 and k_2 are factors accounting for the increased exposure due to distance to ground and detailing, respectively. The reference dose D_0 describes the exposure of a side-grain face of spruce, without accounting for effects stemming from detailing or distance to ground. In other words, D_0 accounts only for the ambient climate and sheltering effects such as roof eaves.

The dose is a cumulative metric increasing with a rate depending on the conditions for fungal decay in terms of daily average wood moisture content and temperature, according to the model proposed by Isaksson et al. [3]. Here, the moisture content is calculated from humidity, temperature, and precipitation through a time-lagged artificial neural network developed by Hosseini et al. [2]. Incident precipitation, which is used as model input, is calculated by simplified climate analysis developed by Niklewski et al. [1]. The effect of exposed contact faces and distance to ground are considered by factorization. In other words, parts of the geometry which are affected by these factors are identified from geometrical relations and an algorithm for detection of contact faces. For example, end-grain surfaces are mapped based on the direction of object's (local) surface normals. Finally, distance to ground is determined by finding the closest distance to the ground surface. Factors are then applied over the geometry depending on these maps.

3. Results and discussion

Figure 1 shows maps of reference dose (left), k_1 (centre) and k_2 (c). The reference dose depends on weather, orientation, inclination, and sheltering effects. To obtain the combined exposure, D, the reference dose is multiplied by factors k_1 and k_2, for each point on the geometry. Factor k_1 is determined by the distance to ground by the relationship from Isaksson et al [4], where wood located more than 300 mm from the ground is unaffected. There are multiple types of detailing, but as a simplification they can be categorized in four types, depending on grain direction (end-grain, side grain) and drying conditions (contact/free). For example, and as indicated in the figure, side grain in contact with another element will increase the dose by a factor of 1.4 according to the same reference.

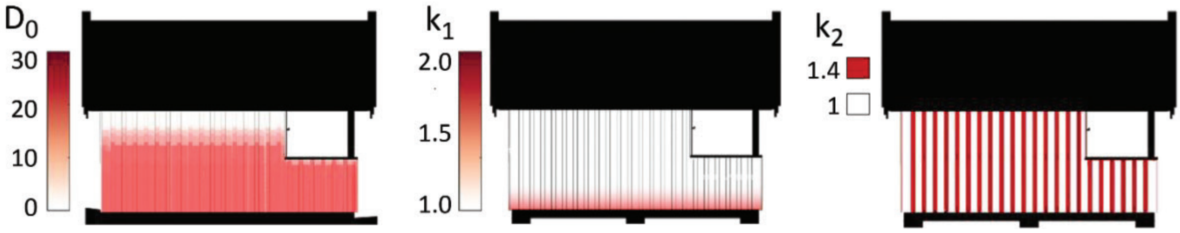

Figure 1 Results showing the reference dose (D_0, left) and the effects of distance to ground (k_1, centre) and contact faces (k_2, right).

4. Conclusions

Decay assessment of a detailed geometry was accomplished by climate analysis, moisture prediction with a data-driven model and a dose model. Distance to ground and contact faces were mapped out over the geometry, to be used for post-processing the dose through factorization. The work is part of an effort to provide architects and engineers with a simple procedure for assessing the service life of wood from detailed 3d geometries.

5. Acknowledgements

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Bioinspired living coating system for regenerative and circular architecture

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Summary

Materials exposed outdoors are prone to various deterioration processes. Architectural coatings are designed to protect surfaces against environmental and biotic degradation and/or to provide a decorative layer. Common surface treatments often include mineral oil binders and other ingredients that are known to have negative impacts on the environment. An alternative bioinspired concept for materials protection based on fungal biofilm is under development. This paper presents the first results related to the bioreceptivity of building materials and the initial steps of natural biofilm formation.

Key words: bioinspired coating system, bioreceptivity of building materials, early fungal colonizers, engineering living materials

1. Introduction

Bioreceptivity is defined as the ability of a material to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration. An understanding of kinetic microbial colonisation on façade materials is indispensable to revealing organism-material interaction and developing a new concept for material protection. An example of such an alternative coating system based on a controlled and optimised fungal biofilm is currently under development within the frame of the ARCHI-SKIN project. In the first phase the morphological, functional, and social interactions in fungal communities naturally appearing on building materials are deeply investigated. The assessment of a variety of fungi that can thrive on exposed surfaces and understanding their interactions with various building materials is crucial to identify fungal species with a protective potential.

2. Methods

A set of 33 wood-based cladding materials were exposed to four cardinal directions and monitored in outdoor conditions on the roof of the InnoRenew CoE building, situated in the coastal town of Izola, Slovenia (45.5350, 13.6577). Multi-sensor and multi-scale measurements were performed to assess the influence of surface properties (wettability and roughness) and material structure on fungal growth, species variability, and dominance. Hyperspectral imaging (HI) as a high-throughput method was used to understand the effect of fungal growth on material properties as well as to objectively quantify the infested area. To evaluate microbial growth, the surfaces were sampled using the wet swab and plated on DG-18 agar, which prevents the growth of bacteria and limits the growth of fast-growing fungi. Pure cultures of dominant species were then isolated and identified through polymerase chain reaction (PCR) amplification and Sanger sequencing of specific DNA regions/genes.

3. Results and discussion

Both the material type and the climate condition at the exposure site influenced fungal colonisation. To investigate the occurrence of dominant species in more detail and in a more quantitative manner, samples where $\geq$ 90% of the colony forming units (CFUs) appeared to have the same morphology were identified at the 1-month timepoint. Pure cultures were obtained and selected DNA regions (internal transcribed spacers 1 and 2 including the 5.8S rDNA (ITS) and/or actin and/or β-tubulin) were sequenced to allow for identification (Fig.1). On most of the investigated materials where a dominant morphology was present, *Aureobasidium* sp. was the dominant genus, implying that *Aureobasidium* can establish dominance already during the early phases of colonisation.

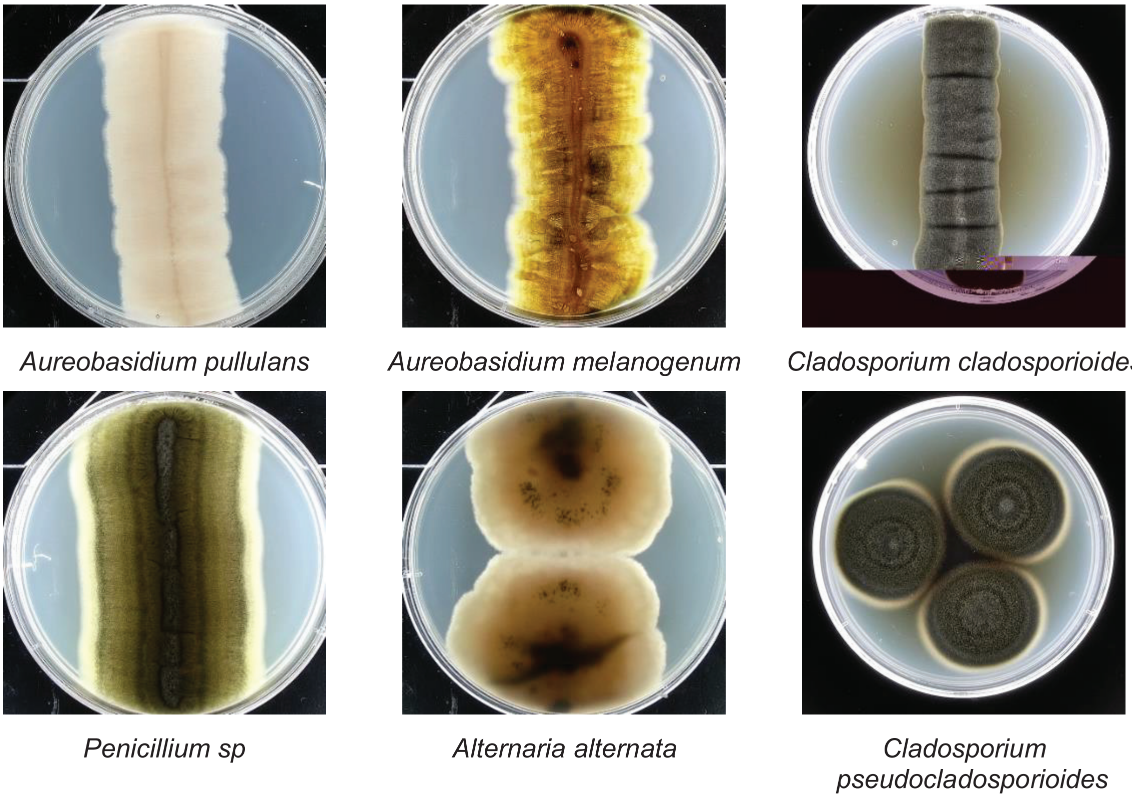

Figure 1 Images of pure cultures.

4. Conclusions

Proposed techniques enabled the identification of features that promote/inhibit fungal colonization and revealed the preference of certain fungi for specific materials. Both the material type and the climate condition at the exposure site influence fungal colonization and the variability of microorganisms. The samples in close spatial proximity exhibited different fungal microbiota, demonstrating that fungal colonization across samples is not random. This study is a starting point for assays that aim to develop novel solutions for materials protection based on controlled and optimized fungal biofilm formation.

5. Acknowledgements

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Tool development for LCC of wooden building envelope

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Summary

The main goal of this study is to provide a platform for LCC calculation rules that comply with the Standards EN 16627:2015 and EN 15643-4. The database includes economic data for the building envelope at the product level and construction, in addition the use phase of the building, including maintenance, and all the relevant economic data related to design failure, user preferences, and technical defects due to moisture.

WoodLCC project is going to implement advanced method to calculate accurate technical service life and give the users the opportunity to evaluate the cost differences based on their choices.

Key words: Life-Cycle-Cost; Service life; decay; Above the ground; Moisture; Species; Detailing; Orientation; UV effect

1. Introduction

1.1. LCC in general

LCC is one of the basic indicators for sustainability assessment and cost effectiveness applicable in construction. LCC makes it possible to optimize the entire life performance of buildings and other structures. While LCC is not yet used to its full potential – mainly due to a lack of reliable data that can be used as input instead of guesses and estimates. In contrary, the relevance of LCC finds increasing acceptance and LCC will become obligatory for procurement by tenders not only in the public sector. Increasing interest in the construction industry and the understanding of LCC benefits have led to a growing number of companies adopting the methodology. LCC is also being applied by an increasing number of public authorities across the EU. The 'EU public procurement Directive 2014/24/EU', encourage the use of LCC as a tool to get the 'most economically advantageous tender (MEAT). As LCC is widely adopted, the guidelines are being refined.

1.2. LCC standards with building in focus

Economic performance is standardized in different levels for building sector. The LCC standards with buildings in focus are: 1) EN 16627 (2015) Assessment of economic performance of buildings, is developed based on ISO 15686-5 and adapted for sustainability assessment in the European context. This standard is used in building level. 2) EN 15643-4 (2012) Economic performance at framework level. The economic performance of a building is only one aspect of its sustainability. The environmental performance (EN 15643-2) and social performance (EN 15643-3) of the building are also aspects of sustainability that are assessed as part of a sustainability assessment of buildings; general framework (EN 15643-1).

1.3. LCC input, especially for wooden material

LCC requires a detailed and comprehensive knowledge of the service life, the expected maintenance interval, and the costs of the products and labour. A major weakness in LCC is the lack of detailed and relevant information on service life estimates, and the expected maintenance, repair, or replacement intervals. Currently, LCC user software is employing simplified default service life estimates, especially for wood products in exterior applications, which in turn can lead to wrong decisions and negative economic and environmental impacts.

Wood has traditionally often been perceived as a material lacking durability. Today, there are numerous options for fulfilling the performance requirements of external building elements made of wood, ranging from utilizing natural durability, chemical treatments, modification processes, surface treatments, etc. Engineered and mass timber products, which are often applied without chemical wood preservation, can provide sufficient longevity if modern architecture involves protection by design, but complex service life prediction models are needed to generate input data for LCC, which are still sparse today. WoodLCC is going to solve some aspects of inaccurate input data in a user-friendly tool.

2. Methods

A data structure is created based on the necessary indicators and parameters for LCC calculation. In this project, wooden material used for building envelope is considered; bearing system, outer walls and façade, doors and windows, outer roof (flat or angled) both for bearing system and roof terrace or thatching, and balcony.

All material price data and installation time for each material is taken from a Norwegian dataset (Prisdata). This data is then modified for the selected European country using country specific labour cost- and material cost-indexes. Inflation and escalation rates are considered for calculating the maintenance or repair that will occur in future. Material price for different species and modification are included.

Lifetime of the outdoor materials are a function of 1) location to determine the UV exposure and annual precipitation, 2) detailing to determine moisture trap in connections 3) shelter and its size that affect the rain exposure. Bearing elements suppose to stay in place for the reference study period unless they prone to moisture trap as an accident.

The total construction cost is calculated once for the selected country. Maintenance cost including major replacement will be calculated by having replacement intervals and considering the price elevation in future.

3. Results and discussion

The model is a robust and user-friendly Excel tool for LCC calculation based on accurate technical service life. In addition, the model includes aesthetic service lifetime based on a survey from user perspective and will be able to give the users indications on how their choices could influence the life-cycle-cost of a building. The model will provide insight for a demo software development which is planned at the end of the project.

4. Conclusions

Improved service life input data will enable more precise and robust LCC for wood-based products, resulting in significantly improved economic and environmental impact. LCC finds common acceptance only if reliable input data are available and complemented with knowledge about user expectations. In addition to technical data, user preference will be adopted to evaluate the effect of aesthetic choices versus technical lifetime choices on the life-cycle-cost. Therefore, a holistic approach will be used to integrate service life data in LCC analysis.

5. Acknowledgements

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The Effect of Material Selection, Design, and Construction on the Service Life and Appearance of a Wooden Building

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Summary

Traditional and historical wooden buildings, known for their durability, have adhered to traditional guidelines for diverting rainwater and moisture from wooden surfaces while receiving regular maintenance. This research aims to evaluate the impact of current design practices, which encompass various non-traditional solutions and details, on the service life of wooden buildings. The findings of this study emphasize the importance of proper coating selection, maintenance practices, and designed solutions to mitigate damage and ensure the longevity of modern wooden buildings.

Keywords: Design, Maintenance practices; wooden building; service life.

1. Introduction

Traditional and historical wooden buildings, known for their longevity and continued existence, have adhered to traditional guidelines aimed at diverting precipitation and moisture away from wooden surfaces, along with receiving consistent maintenance. Examples of such guidelines include having wide eaves and high plinths, among others. Current design practice, in contrast, incorporates numerous non-traditional solutions and details. This research assesses the parameters such as material quality, design level, and work execution level on the service life of wooden buildings. More specifically, the focus of this study lies on the effect of current design practices on the building maintenance interval and the appearance over time.

2. Methods

This study focuses on the wooden buildings that are submitted to the annual “Wooden Building of the Year” architecture competition. The selection of buildings was made based on the assumption that the wood as the structure and (or) exterior and interior finishing element in the buildings has been used with the best knowledge available. The current technical condition of the buildings was assessed by visiting the selected buildings and later by comparing the photos taken after the building was completed and during the latest visit. By comparing photos, the assessment of building ageing is carried out by targeting buildings that have reached their first maintenance interval (with ages ranging from 8 to 15 years). Data obtained from the visual assessment will be categorized. This categorized data will then be utilized to identify which damages have most frequently occurred and what were their main causes.

3. Results and discussion

The results of this study showed that when using opaque coating, the change in appearance over time is smaller and less noticeable compared to transparent coating, see Figure 1a. This is due to the longer maintenance interval of opaque coating, and it tends to hide wood discoloration in case of cracking, while transparent coatings reveal it. Uncoated wooden facades age naturally, turning grey over time, with their lifespan lasting until replacement is necessary, see Figure 1b. Wooden roofs, depending on the pitch and coating, can have varying service life, with low-pitched roofs requiring more maintenance and having shorter lifespans. Algae growth, flaking of the coating, excess moisture, and moss growth, were among the most common types of damage. Water running onto the facade was identified as the primary cause of damage, followed by UV radiation, splashing water, poor maintenance. Moisture-related damages were mainly attributed to water flowing onto the facade and splashing water. Moss growth was linked to insufficient maintenance, while coating flaking was primarily caused by UV radiation. The classification results revealed that most damage cases stemmed from designed solutions and deficiencies in the integrity of the building project. This underscore shortcomings in the designed solutions aimed at preventing rainwater from flowing onto the facade and managing drainage effectively. Inadequate maintenance practices, focusing on remedying damage rather than preventing it, can significantly impact the durability of modern wooden buildings, leading to higher maintenance costs over time. Misguided selection of coating can result in increased maintenance frequency, subsequently increasing maintenance costs or shortening the service life of the coating.

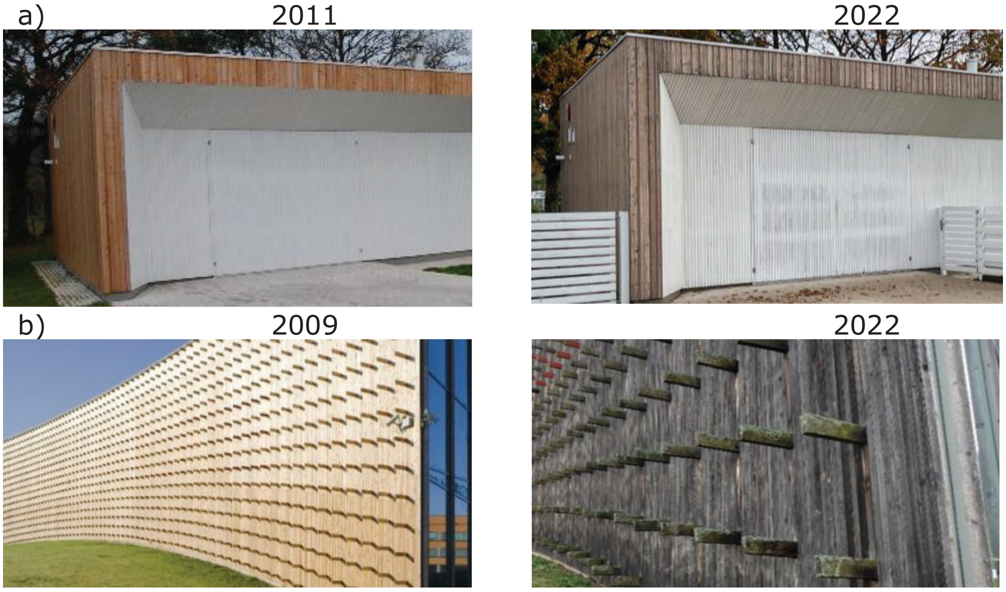

Figure 1 Example of two buildings, one aged 10 years (a) with a coating on the façade and the other aged 12 years (b) without a coating.

4. Conclusions

Opaque coatings result in a smaller change in appearance over time compared to transparent coatings. This is attributed to the longer maintenance interval of opaque coatings. Algae growth, flaking of the coating, and moss growth were identified as the most common types of damage observed. While moisture-related damages were predominantly attributed to water flowing onto the facade and splashing water, flaking and cracking were caused by UV radiation. Most damage cases stemmed from designed solutions, followed by inadequate maintenance practices, which can significantly decrease the durability of facades and exterior details of observed modern wooden buildings. Misguided selection of coating can lead to increased maintenance frequency, subsequently raising maintenance costs or shortening the service life of the coating.

5. Acknowledgements

This work has been supported by the Estonian Research Council through the grant PRG483; ERA-NET Cofund ForestValue (in the frame of the research project WoodLCC), which has received funding from the European Union's Horizon 2020 research and innovation programme (Reference: MNKE22024); and by European Commission through the LIFE IP project BuildEST (Reference: LIFE20 IPC/EE/000010).

FORUM WOOD BUILDING BALTIC

MOISTURE SAFETY

Determining Moisture Content of Laminated Veneer Lumber (LVL)
Inger Merete Birkeland, Erlend Andenæs, Lars Gullbrekken, Tore Kvande

The future of wooden structures in combination with bio-based insulation
Anke Blommaert, Nathan Van Den Bossche, Marijke Steeman

A numerical study of methods to improve moisture safety of ventilated wooden roofs
Klaus Viljanen, Laurina Felius

Moisture safety strategies for roof renovation with prefabricated additional insulation elements
Georg-Mihkel Kodi, Kristo Kalbe, Peep Pihelo, Targo Kalamees

A novel approach to quantify crack formation in CLT
Kristo Kalbe, Targo Kalamees

Determining Moisture Content of Laminated Veneer Lumber (LVL)

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Summary

The purpose of this study is to investigate the moisture properties of LVL and the correlation between moisture sensor readings and the actual moisture content determined from accurate weighing of the samples. Laboratory measurements were made of two different wooden materials using 20 identical sensors. The test was conducted on samples of LVL flanges and samples of pine lumber. The test results show for the LVL samples, that the resistance values given by the resistance method were too high compared to the more accurate gravimetric method. Conversely, the measured values were too low for the pine and spruce samples.

Key words: Building physics; Structures and materials; Moisture Introduction

1. Introduction

This paper examines the differences between measuring moisture content by the gravimetric method and the resistance method, respectively, and possible causes of these differences. It also investigates the difference between the moisture content of mixed spruce/pine LVL and pine lumber (*pinus sylvestris)* according to the resistance method, and whether the glue between the veneer layers in LVL can affect the conductivity of the material.

There are two assumptions made in the gravimetric method: that the water is completely removed by oven drying and that only water is removed, and that no other parts of the material are affected during the measurement period.

This paper examines the following research questions:

1. What are the differences between the measured moisture absorption in LVL and pine?
2. To what extent do the resistance method and the gravimetric method give different results for the two materials?
3. What causes electric resistance measurements of LVL to give different moisture content readings to wood?

The tests were limited to investigating moisture absorption properties, as desorption studies were deemed infeasible, given the practical constraints of the study. Scots pine (*pinus sylvestris)* lumber was used as reference sources, which may cause results to deviate slightly from studies conducted of southern yellow pine (SYP) or other spruce lumber. Only one type of electric resistance sensor was used in the research. The main motivation for the research was to establish correlation curves in order to evaluate the moisture performance of the compact wooden roofs with smart vapour barrier pilot projects going on in Norway.

2. Methods

The paper is based on a laboratory experiment and a literature search concerning moisture in wood. Laboratory measurements were made of 20 pieces of wood. The test was conducted mainly on the LVL, but also on six pinewood samples, to compare the results.

The laboratory measurements took place in the lab of SINTEF and NTNU in Trondheim. By placing the test samples in different climates, between 23% to 98% relative humidity (RH), data from the sensors and from weighing each sample could be used to determine the connection between the measuring methods. See Figure 1. The system's operating temperature of 23°C is maintained within a tolerance of ± 1°C.The last part of the experiment was conducted by laying the wood samples in liquid water to find the absolute moisture content. To gain the hysteresis effect, the same test samples were moved from one climate to another to examine the moisture values at different humidity with different moisture history.

Figure 1 Omnisense sensor placed in an LVL sample, with the electrodes perpendicular to the grain direction. Also parallel to the grain direction was tested. The nails are not insulated.

3. Results and discussion

LVL appears to absorb moisture faster and to a greater degree than pine. According to measurements, the resistance method will yield too high moisture readings from around 65% RH upwards. It seems evident that the two measurement methods give different results for both the materials examined. For low moisture levels, the two methods were accurate for both materials, but at higher moisture levels the resistance method reported too low RH in pine and spruce, and too high RH in LVL. No significant difference was seen between measurement by the resistance method perpendicular and parallel to the grain direction.

4. Conclusion

Results show that LVL takes up more moisture than pine and that some factors affect the resistance in LVL when the RH goes above 65%. The resistance method then yields a too high moisture content above 65% RH, a deviation that increases on higher RH. Conversely, for pine the resistance method gives a wood moisture equivalent that is around respectively 3 weight-% too low. To achieve a good result on measuring the moisture content of LVL, it is important that there are no holes (knotholes or other imperfections) in the material where the sensors are placed and that the screws are tight. However, this may not always be possible to assess from the surface of the sample.

The literature search shows that the measurements of moisture in LVL are affected by the glue, although thorough investigations into the physical mechanisms have not been conducted in this paper. It is theorised that capillary suction in the interface between the glue and veneer layers may cause the material to absorb moisture more easily.

5. Acknowledgements

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The future of wooden structures in combination with bio-based insulation

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Summary

This study assesses two aspects: the impact of moisture-buffering materials on the drying capacity of the structure, and the impact of climate on the drying process. The assessment is done based on heat, air and moisture simulations in Delphin 6.1.4.

It is investigated whether or not the use of a moisture buffering insulation material has an influence on the drying capacity of different wooden structures and if the drying capacity differs for different climate projections.

Key words: Bio-based insulation; Building physics; Climate change; CLT; HAM simulations; Hygrothermal behaviour; Wood frame construction.

1. Introduction

The use of bio-based materials gain popularity thanks to their small carbon footprint [1]. However, because of the natural origin of bio-based materials, an exposure to unfavourable moisture and temperature combinations could lead to higher concentrations of insects, fungi or bacteria possibly resulting in mould growth or degradation of the cell structures. On top of that, these materials are able to store moisture over time. Both the moisture buffering capacity and the possible change in pore structure due to mould growth could alter the thermal performance. Since both of these are influenced by moisture, it is important to gain more insight into the moisture content in constructions using these kinds of materials.

Not only is it important to know if bio-based insulation performs different than mineral wool or PUR, it is also useful to know how these materials would hold up in the future. Climate projections are used to investigate their performance for different mitigation scenarios.

2. Methods

This study starts form two wall configurations: a timber frame wall using mineral wool as insulation material and a CLT wall using PUR as insulation material. This study compares these configurations with a similar build-up, but using cellulose as bio-based insulation material. Also the ventilation rate of the cavity behind the façade cladding is varied (ACH of 100, 200 and 400 1/h).

Four different climate datasets were analysed: historically measured data from Brussels (1972-2005) and three different climate projections for 2066-2099 each taking into account a different Representative Concentration Pathway (RCP). [2] [3] [4] The different RCP scenarios include a strong mitigation scenario (RCP 2.6), an intermediate scenario (RCP 4.5) and an extreme high emission scenario (RCP 8.5). The values 2.6, 4.5 and 8.5 represent the radiative forcing in W/m² by the end of the 21st century, the change in energy flux at the top of the atmosphere. [5] The climate data originate from the ALARO-0 RCM driven by the CNRM-CM5 GCM. [6] [7] Note that the used climate datasets contain a 34 year period of which the first 4 years are used as conditioning period.

The damage mechanism that is evaluated in this study is mould growth. The mould growth risk is evaluated according to the improved VTT-model [8]. Mould growth will only occur on the outer faces of the materials. However, the mould index is also used as an indicator for other possible damage mechanisms due to moisture. As moisture content is expected to be the highest in the outer area of the insulation layer, this study also evaluates the mould index at additional points near the outside surface.

3. Results and discussion

For all climate scenarios analysed, the mould index is the highest for an ACH of 100 1/h. Figure 1 shows the average mould index at location A for the four climate scenarios for ACH 100 1/h.

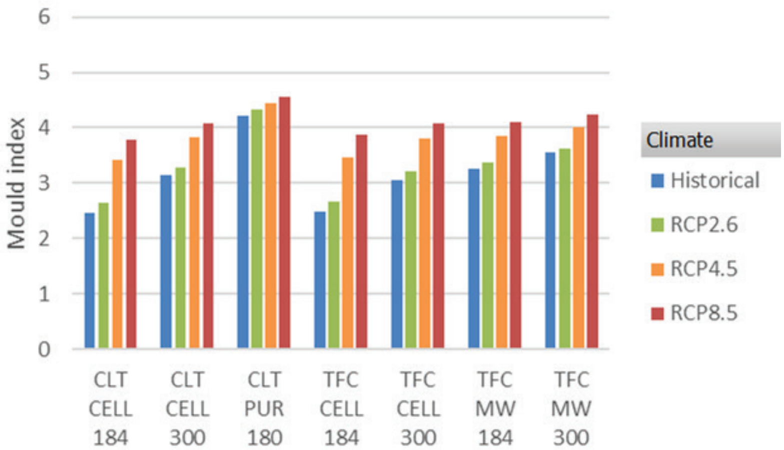

Figure 1 Mould index at location A for the different wall types with ACH 100 1/h for different climate scenarios. (CLT = Cross Laminated Timber, TFC = Timber Frame Construction, CELL = Cellulose, PUR = Polyurethane, MW = Mineral Wool, the third line gives the thickness of the insulating layer in mm)

The figure shows that a higher mitigation scenario leads to a lower mould index compared to higher emission scenarios. This is probably due to the temperature increase which is beneficial for mould growth. This conclusion is valid regardless of the construction type (including the type of insulation material).

For all climate scenarios the mould index for cellulose is lower than its traditional counterpart insulation material (mineral wool or PUR). However, with increasing emission scenarios, the difference between the bio-based and traditional insulation materials becomes smaller. For timber frame constructions, the difference in mould index between mineral wool and cellulose insulation almost completely vanishes for the highest emission scenario. This is caused by the fact that this climate scenario has a bigger impact on the mould index for cellulose insulation than for PUR or mineral wool. For example, in a timber frame construction with an insulation thickness of 300 mm, when looking at the climate scenario RCP 8.5 compared to historical climate, the mould index increases with about 32% when insulated with mineral wool while the mould index increases with more than 60% for cellulose insulation.

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A numerical study of methods to improve moisture safety of ventilated wooden roofs

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Summary

The hygrothermal performance of highly insulated, prefabricated wooden roof structures is likely to deteriorate due to the low heat flux to the ventilation cavity. This article evaluates the possibility to improve the moisture safety of such roofs in Nordic climate by using different control methods for the ventilation rate of the roof and by using thermal insulation above the roof sheathing. The results support the use of adaptive roof ventilation as it decreases the probability of mould growth in the roof. The use of thermal insulation above roof sheathing decreases the probability of mould growth only slightly in a roof with elevated amount of built-in moisture.

Key words: Wooden roof; Controlled ventilation; Hygrothermal performance; Nordic climate

1. Introduction

Strict requirements for the thermal envelope in the Nordic countries require highly insulated roof structures, which have an increased moisture risk compared to less insulated structures (Viljanen 2023). As the thermal conditions in the cold season in the ventilation cavity of the roofs are close to the outdoor air, the moisture conditions in the cavity may deteriorate even with a small moisture load directed to the cavity (Viljanen 2023). Moisture issues in the ventilation cavities of roofs with a low thermal transmittance may become more common in the future as a result of climate change (Harderup & Arfvidsson 2013, Nik et al. 2012).

The hygrothermal performance of roofs may be improved, for example, by designing the roof ventilation and the level of thermal insulation above the ventilation cavity (Viljanen 2023). This study numerically assesses the moisture safety of wood-framed, prefabricated roof elements in the current Finnish climate, and analyses the possibility to improve the moisture safety by controlled ventilation or using insulation above the roof sheathing.

2. Methods

The studied roof is a wood-framed, mineral-wool insulated, prefabricated roof element with a thermal transmittance of 0.09 W/(m^{2}K). The element includes a 100 mm high ventilation cavity above the insulation. The roof sheathing is a plywood board with bitumen roofing. Alternatively, there was an additional 20 mm mineral wool board above the roof sheathing.

The two-dimensional, time-dependent hygrothermal model was implemented in the commercial software Comsol Multiphysics. The numerical roof model was validated based on the analytical solutions of heat and moisture transfer in the ventilation cavity. The probability of mould growth in the outer parts of the roof was evaluated based on the

Finnish Mould Growth model. The weather conditions in the simulation were according to the reference year Vantaa 2017 representing the current weather in Southern Finland.

The air velocity in the ventilation cavity was directed from left to right and it was determined according to the following scenarios:

- Constant air change rate (ACH) in the cavity (5 1/h or 50 1/h)
- Constant ACH in the cavity (50 1/h) when the outdoor relative humidity is below 75 %. Otherwise, the ACH is 5 1/h.
- Constant ACH in the cavity (50 1/h) when the absolute humidity in the roof is above the level of the outdoor air. Otherwise, the ACH is 5 1/h.

3. Results and discussion

The numerical results show that additional thermal insulation above the roof sheathing slightly increases the drying rate of the mineral wool. If the level of built-in moisture in a roof is elevated, the risk of mould growth is in the direction of the ventilation airflow near the air outflow. The drying rate of the roof is slower in autumn weather than in the winter.

The ventilation rate is an important factor for the mould growth risk in the cavity. A higher ventilation rate only when outdoor relative humidity is below 75 % showed improved performance compared to the constant ACH of 50 1/h. This result is in accordance with the observation by Viljanen 2023 that the optimal ventilation rate of roofs is about 20 1/h considering both the moisture safety and the risk of snow melt.

The adaptive ventilation that compares humidity content in the roof and in outdoor air showed improved performance and reduces the risk of mould growth in the roof. Hygrothermal models with adaptive ventilation may be slow to solve which limits the number of variables to study. These models may also suffer from convergence issues and averaging of the boundary conditions is usually required.

4. Conclusions

This study assessed the factors affecting the moisture safety of wood-framed roof elements in Nordic climate. A high level of built-in moisture in a wooden roof element leads to a risk of mould growth in the middle area and in the outflow area of the roof. In some cases, a high level of roof ventilation may prevent this risk. The use of adaptive roof ventilation proved to be a promising approach decreasing the risk of moisture issues in a roof. In practise, such an approach requires to use, for example, fans and measurement sensors. Although thermal insulation above roof sheathing does not prevent mould growth risk in a roof with high amount of built-in moisture, this approach improved the hygric performance of the roof. The numerical model developed for the study proved to describe the hygrothermal behaviour of a roof reliably. Future studies should analyse the behaviour of the wooden roof elements also in the predicted future weather conditions.

5. Acknowledgements

The authors gratefully acknowledge and thank Rambøll for financial support.

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Moisture safety strategies for roof renovation with prefabricated additional insulation elements

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Summary

Automating the renovation process and using prefabricated additional insulation elements could be a solution to achieve deep renovation goals. Building renovation with prefabricated elements is not only a matter of energy performance but also involves several hygrothermal challenges. Installing prefabricated roof elements by using temporary roof (during construction) is complicated or even impossible. This study presents the possible moisture failures during renovation of roof with prefabricated insulation elements without proper moisture safety measures and develops a strategy to guarantee moisture safety in future renovations.

Key words: Prefabricated additional insulation elements; Moisture safety; Deep renovation; Offsite serial renovation.

1. Introduction

To fulfil nearly Zero Energy Building requirements, the thermal transmittance of the building envelope must decrease 2 – 20 times depending on the climate and existing properties of the building envelope. Today, the rate of energy renovations is not high enough to fulfil the ambitious goals set. Automating the renovation process and using prefabricated additional insulation elements for façade and roof could be one of the solutions to increase renovation speed and achieve deep renovation goals.

If the roof structure is opened to install insulation in the regular way, the building is no longer protected from precipitation. Installation of prefabricated insulation elements allows renovation without opening the roof structure. Nevertheless, precipitation during the installation still poses a risk and moisture may remain in load bearing structures or other materials in the attic. Therefore, renovating the roof requires different moisture safety solutions than the façade.

2. Methods

The case-study building is a typical five story concrete large panel apartment building (series 111–121, total area 4318 m²), constructed in 1986 (Figure 1) and renovated to nearly zero energy building (nZEB) by using prefabricated façade and roof elements. The sloped roof insulation elements were installed on an additional timber frame to remove the original inward slope and parapet. A new attic crawl space (0.6 – 1.2 m high) formed between the existing and the new sloped roof (with 340 mm of mineral wool insulation). Bitumen waterproofing on the external side of the existing roof was retained to be a temporary water barrier during renovation. Additional mineral wool sheets were installed over the bitumen to achieve lower combustibility of the attic surfaces. During the construction of the new roof, rainwater accumulated into the mineral wool on the attic floor and started to evaporate after the completion of the roof. This caused high relative humidity (measured with data loggers) and mould growth on the wooden surfaces in the attic crawl space, especially on the interior surface of the new roof elements. Surface mould growth was detected first visually and later using a stereomicroscope with samples taken from selected locations. New moisture safety strategies were proposed. The different strategies were examined and compared by implementing whole building indoor climate and energy dynamic simulation with IDA Indoor Climate and Energy software.

Figure 1 Overview of the case-study building during nZEB renovation with prefabricated timber frame insulation elements (above) and installation of roof insulation elements (below).

3. Results and conclusions

Visual signs of previous high water levels on the attic floor and mould growth was found during the first month after the end of construction. Mould started to grow mostly on oriented strand boards (OSB). All materials affected by mould were replaced to prevent residents' health issues due to possible movement of mould spores from the attic to living rooms. Surface contamination measurements were repeated three years later in 2021. The attic ceiling surfaces were then mainly free from mould growth.The measured and modelled temperature and humidity conditions showed good agreement suggesting that IDA-ICE software is suitable for such an analysis. Different strategies were sampled to simulate situations that would prevent mould growth or any moisture damage in the attic: construction in dry conditions (temporary roof); using ventilation to eliminate local excessive water damage on the attic floor; using ventilation and heating or using air dehumidification to eliminate damage. IDA-ICE software makes it possible to calculate the drying out of built-in moisture with sufficient accuracy and to develop moisture security plans. The calculated mould index coincided with the situation that was detected on the site, so the mould index is a good indicator for evaluating the construction moisture safety. Dry construction is the best and safest option. Careful work and quick response might be possible with a knowledgeable team and a well-analysed action plan. Simulations suggest that the required air flow for drying via ventilation without heating is 0.5 – 0.55 l/(s·m²) and 0.4 l/(s·m²) with heating.

The moisture safety commissioning for renovation using prefabricated timber frame roof insulation elements highlighted the need for rigorous inspections, strict moisture safety regulations, and thorough analysis of prefabricated insulation solutions in renovations.

4. Acknowledgements

This work has been supported by the Estonian Research Council through the grant PRG483 and by the European Commission through the LIFE IP BUILDEST (LIFE20 IPC/EE/000010) and H2020 project oPEN Lab (Grant agreement ID: 101037080).

A novel approach to quantify crack formation in CLT

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Summary

Manual measurement of cracking in cross laminated timber (CLT) is complex, yet quantifying cracking density accurately is necessary. This paper presents a novel image processing method to quantify crack formation in CLT. Validation using CLT test specimens demonstrated the methods' efficiency, yielding quick and precise results. The experiments confirmed that contact with free water increases cracking in CLT panels, highlighting the necessity to avoid such exposure. The image processing workflow is viable for usage in quality assurance and is worth developing further in future scientific studies.

Key words: Moisture Safety; Image Processing; Building Physics; Timber; Cracking

1. Introduction

During construction, cross laminated timber (CLT) panels are frequently exposed to excessive levels of moisture, leading to fluctuations in the moisture content (MC) of the panels. This in turn causes formation of cracks in the CLT. Prior research has established a connection between CLT and air leakages, particularly in areas where the panels got wet during construction. Such air leakages could compromise the hygrothermal performance of the entire construction assembly. Moreover, cracks have a negative impact on the visual aesthetics of CLT panels if the panels serve as the final indoor finishing layer. Hence, studying crack formation in CLT panels and potentially proposing a new performance criterion based on timber MC to prevent cracking are necessary. However, it is cumbersome and prone to error or even unfeasible to measure the cracking extent manually (e.g., with a ruler) on larger surfaces. This paper introduces a novel method to quantify the crack formation in CLT through image processing and presents results found by the system on the correlation between wetting and cracking of CLT panels.

2. Methods

Cracks in CLT may appear as widened and relatively uniform gaps between the CLT lamellas or irregular cracks in the middle of the lamellas. The latter are especially difficult to quantify with manual methods. However, the cracks appear darker than the surfaces of the CLT panels' faces, as the insides of the cracks are in shadow if the panels' faces are lit appropriately. This observable fact provides a basis for the image processing system – it is possible to count pixels based on a predefined condition – such as the colour or luminosity of the pixels (e.g. black or dark pixels which correspond to the shadow areas).

To validate the method, 40 cm by 40 cm CLT test specimens (TSs) were extracted from a larger panel and categorised into two groups: TSs which were exposed to bulk water and subsequently dried and other TSs which remained dry throughout the test. MC in all TSs was equal at the time of photographing. The camera was equipped with an APS-C size sensor and a 50 mm lens. Every photo was made with the same manual settings from the same distance. Bright overhead lighting was used to emphasise the shadows in the cracks and all images were converted to black and white to further increase contrast. Knot areas were masked out in post processing to avoid erroneous crack detection. Next, an image processing script was developed in R, using the package countcolors. The developed program can count the number of pixels corresponding to the cracks and output images where the determined cracks are marked with contrasting colour, which is useful for validation of the results (Figure 1, top left).

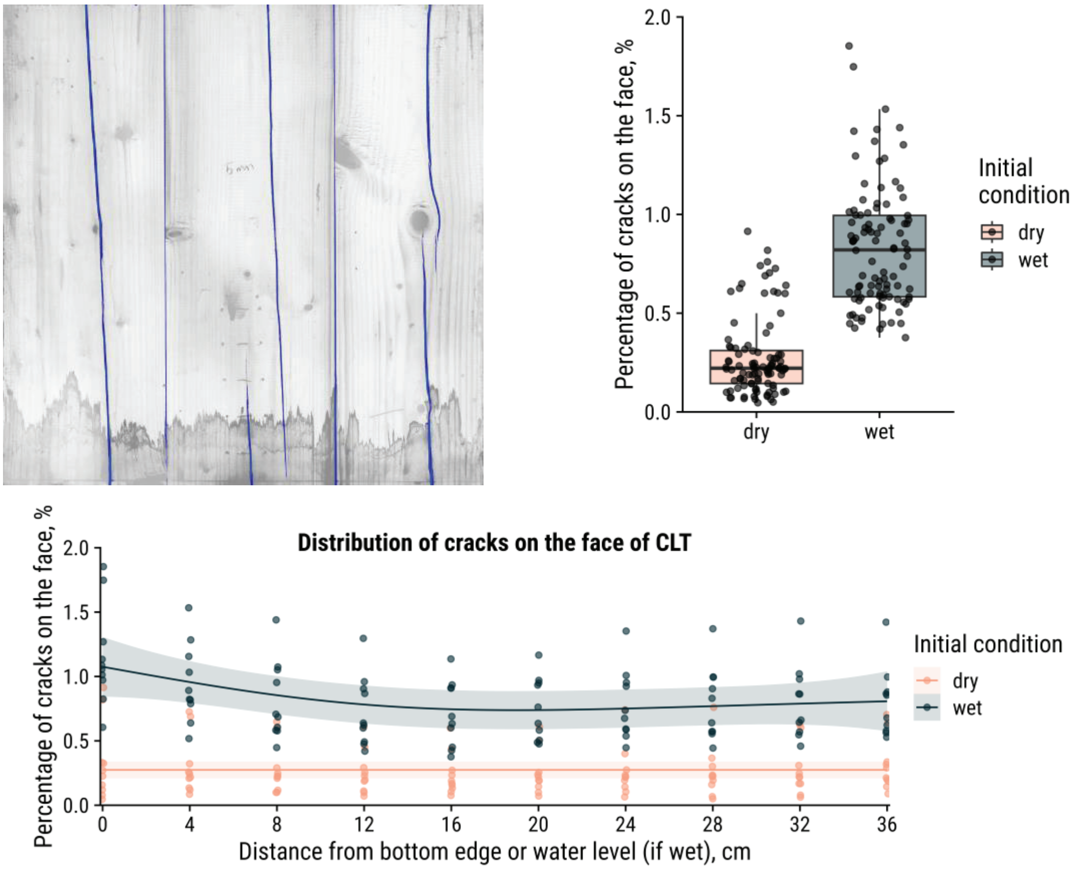

Figure 1 Example image of a CLT panel (top left) where the algorithm has automatically found and marked cracks with contrasting blue colour. The calculated crack area (top right) was larger in the details which got wet. Within a wet panel, the crack area was larger on the surface nearer to the water contact surface (bottom).

3. Results and conclusions

The image processing method demonstrated effective functionality, yielding meaningful results. The photo system was easy to set up and automated input to the R script allowed bulk processing. It was evident that the crack area in the CLT panels which were subjected to free water and then dried was significantly higher than in those panels which remained dry throughout the entire test period. Although the overall outcome is visible to the naked eye, it is now possible to quantify the crack area very precisely and quickly. The average crack area in the wetted panels was three times larger than in the dry panels. Moreover, the crack area within the wetted panels was larger nearer to the surface which was exposed to free water while the crack area was uniform throughout the entire panel in the dry test specimens. This difference in crack area within a CLT test specimen was too subtle for visual determination, but the newly developed method facilitated clear identification. Contact with free water evidently increases the cracking in CLT panels and should be avoided. The image processing workflow is suitable for usage in practical quality assurance with little additional effort or in future scientific studies. For example, precise crack detection could be beneficial for determining the MC value when excessive cracking occurs.

4. Acknowledgements

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FORUM
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TIMBER STRUCTURES

Reconnect Ukraine – research project on timber connections
Andrii Bidakov, Robert Jockwer, Alar Just, Eero Tuhkanen, Dmitrii Kochkarev

Assessment of strength and stiffness properties of aged structural timber
Maarja Kauniste, Alar Just, Eero Tuhkanen

Bending and vibration behaviour of CLT-steel composite beams
Noah Böhm, Bertram Kühn, Achim Vogelsberg

On-site application of end-grain bonded timber under low curing temperatures
Dio Lins, Steffen Franke

Reconnect Ukraine – research project on timber connections

Andrii Bidakov, Assistant Professor[1]; Robert Jockwer, Assoc. Professor[2]; Alar Just, Professor[3]; Eero Tuhkanen, Assistant Professor[4]; Dmitrii Kochkarev, Professor[5].

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Abstract

The project presented in the paper aims at the development of a new solution for an universal connector in CLT timber structures, which offers the possibility of quick and easy installation and assembly, as well as easy disassembly and reuse. This solution shall contribute to the necessary reconstruction of the damages in Ukraine and facilitate the quick restoration of housing as well as providing a long-lasting sustainable and circular connection solutions. The developed connector is a unit in the form of a steel plate on glued-in rods, that are embedded in the CLT panels. This allows to connect CLT panels in various arrangements together or to other building parts such as foundations or concrete cores. Connections with glued-in rods are widely used in Eastern European countries, especially in long-span timber structures for buildings of various types.

Key words: glued-in rods (GiR), bonded-in rods, combined loading, group effects, universal joint, CLT panels, connector.

1 Introduction

1.1 Background

The construction sector is responsible for a significant share of Green House Gases emissions (ca. 30-40%) and raw material consumption (ca. 50%) globally. Building with timber and the shift of the construction sector towards a circular economy are key elements to success in order to achieve a more sustainable built environment and a more sustainable society.

One of the barriers for the greater utilisation of timber in construction is that engineers, architects, contractors, and authorities have little experience with the construction material timber and its utilisation in high-performance structures compared to other conventional building materials such as concrete and steel. Often the experience, skills, and workmanship regarding timber on the construction site are limited. Besides training also the development of simple connection and detailing solutions need to be developed, that can be easily and safely applied by unskilled personnel. Prefabricated connections with bonded-in rods or bolted connections are examples of such solutions.

In their development it as to be put emphasis on long-lasting sustainable and circular solutions instead of unsustainable single use solutions of buildings. Adaptable buildings that can be extended over time are suitable to provide quick shelter for many and allows the further extension when recourses are available. Modular prefabrication of elements allows the fast production, construction, and even reaction to local demands.

1.2 The project ReConnect

In the project ReConnect - Efficient connections for modular prefabricated timber buildings to help reconstruction in Ukraine, that is funded by Sveriges Institutet, the partners from O.M.Beketov National University of Urban Economy in Kharkiv (Ukraine), Chalmers University of Technology, Gothenburg (Sweden), Tallinn University of

Technology, (Estonia), and National University of Water and Environmental Engineering in Rivne (Ukraine) are collaborating.

The project has the objective to develop a novel connection system for timber members that makes it possible to adopt the concepts of reusability, adaptability and circularity of members in timber structures. By optimizing the connection layout, we intend to enhance the performance towards low damage and to avoid brittle failure modes in the timber. The project will reduce the complexity of high-performance connections for timber buildings and lower the entrance barrier towards the use of timber in structures.

In an experimental campaign we want to experimentally validate the performance, predictability, universality and reusability of the novel connection system in timber members with different loading situations.

1.3 Application area

There are different examples of connections that can be seen as first steps towards the direction of a universal timber connection systems that allow for high performance, prefabrication, easy application, dis-assembly and reuse. Examples are: Bolts, dowels, screws, or bonded-in steel rods. Especially bonded-in rods allow for a direct transfer of tension forces along the grain direction of the timber. By placing rods at different inclination into the timber, brittle failure in the timber in tension perpendicular to the grain can be prevented and the connection can resist a variety of loading directions. By combining the rods with adequate connection elements into one system, it becomes possible to prefabricate, assemble and disassemble timber components. The rods remain in the timber but the connector element can be easily adapted and re-connected. Such a connection system has to be developed towards predictability of behaviour, universality in application, reusability and efficiency.

The prefabrication of the proposed connection in the factory and its uniform spacing along the edges of CLT panels makes it possible to produce entire series of unified building components of different sizes and layout solutions, see Figure 1. The regular spacing allows that the CLT panels can be prefabricated mostly independent of its later application, and they can be combined in different arrangements in a structure depending on the specific demand. The connector is installed in the side face of CLT panels in a pre-milled recess for the plate and can be completely hidden in the interior or invisible, which is also good in fire conditions.

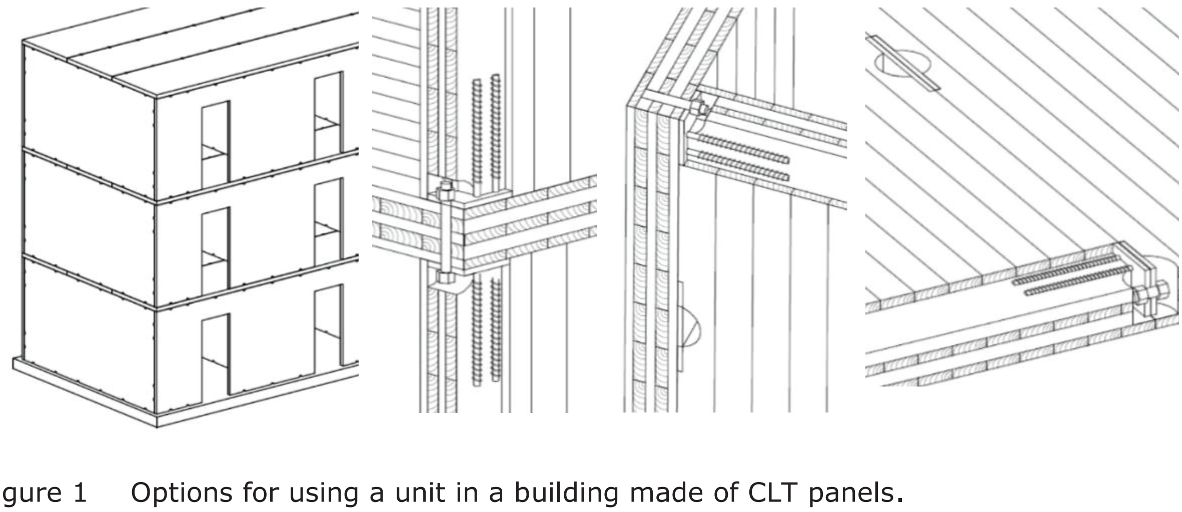


Figure 1 Options for using a unit in a building made of CLT panels.

For the first time, this type of connection for CLT panels was proposed in the frame of the EECTC conference in Kharkiv (Ukraine) in 2018. In the conference proceedings tests of glued-in rods in CLT samples were reported (Bidakov et al. 2018), where pull-pull configuration with different variants for their location in the panel cross section were studied. To date, many laboratory tests have already been carried out on glued-in rods in CLT, both single (Andersen & Høier 2016, Azinov et al. 2018, Azinov et al. 2019, Jockwer et al. 2023, Stepinac et al. 2013) and groups of glued-in steel rods (Ayansola et al. 2022). However, this new connection type requires further laboratory testing on the full connection, since the metal plate can redistribute the actions to the different rods. Depending on the loading condition of the CLT panel and subsequently the connector the rods experience various loading conditions, including complex stress states with simultaneous axial loading with pull-out of the rod and lateral loading with the rod acting as a dowel and stressing the timber perpendicular to the grain. Another possible complex combination of stresses is pullout and torsion.

For an initial assessment of the load-bearing capacity of the connection with the steel plate and glued-in rods in a CLT panel and for the evaluation of the prospects for its serial use, analytical calculations and modelling of a 3-story building were carried out.

The common practice and experience with using glued-in steel rods (GiR) in the CIS countries is very large and in the USSR this connection type was already included in the standard for the design of timber structures SNiP II 25-80 (SNiP 1980). The current draft version of Eurocode-5 (prEN1995-1-1: 2023) (prEN 2023) contains recommendations regarding design of bonded-in rods (BiR) and, hence, opens the possibility of a more wide implementation of BiR solutions in practice. The design standard works together with the testing standard for the bondline strength in EN 17334 (EN 2021), which assures the high-performance and high quality of the BiR solutions.

2 Materials and Methods

2.1 Connector geometry

The proposed type of connection consists of a 12 mm thick steel plate (steel grade S355) to which steel bars RiBa A500C diameter 10 mm are welded. The length of the reinforcing bars is 150 mm. The bars are glued into pre-drilled holes using a two-component epoxy adhesive system, see Figure 2. To distribute the high shearing or pulling forces across the thickness of the CLT panel with its orthotropic and heterogeneous boards, it was decided to use 8 glued-in rods for the connection.

The steel plate has 8 holes for the rods and a centric hole of 27 mm diameter in the middle of the plate for connecting it with a bolt M24 to the other unit in another CLT panel (Figure 3 (b)) or to another CLT panel directly (Figure 3 (c)).

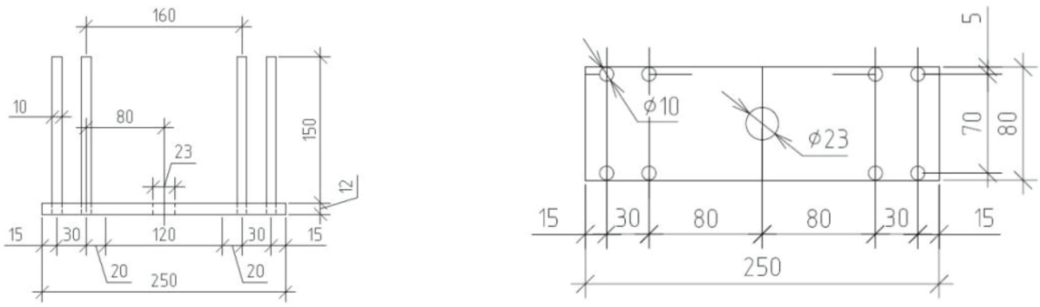


Figure 2 Geometric parameters of the connector.

The connection between the steel plate and the CLT panel is rigid due to the lack of slip deformation in the timber element, and deformations might only occur in bending of the steel plate. This connector can also be attached to reinforced concrete members or foundations. It is also possible to attach such a connector to steel components and structures or even weld them to them with a discontinuous seam. The connector has a semi-circular milled hole in the CLT panel around at 2/3 of its thickness to allow installation of a bolt or nut (Figure 3 (a)).

Figure 3 General view of the installation of the connection (a) and assembly of two units (b) and of the unit directly to CLT panel (c)

This connector unit makes it possible to assemble and connect CLT panels in 6 main cases: a) two floor panels parallel to the span, b) two wall panels in a planar manner, c) two wall panels at the corner of a building (L shape), d) a longitudinal wall panel and a transverse wall or partition wall (T-shape), e) wall panel to the foundation, f) floor to wall joint. It is also possible to attach beams and columns to CLT panels using the proposed unit in combination with glulam beams.

2.2 Possible configurations

The geometric configuration shown in Figure 4 (a) is provided for connecting CLT panels with a thickness of 100-120 mm since the width of the metal plate is 80 mm (see Figure 2) and must be hidden. For CLT panels 120-140 mm (Figure 4 (b) and (c)), it is proposed to use a connector with a plate width of 100 mm, in order to increase the load-bearing capacity of the connection. From a static point of view it is important to reduce the distance from the edge of the panel to the axis of the glued-in rods, which should, however, not be less than 2.5 d according to EOTA TR 070 (EOTA 2019) or prEN1995-1-1:2023 (prEN 2023) in order to avoid splitting. Increasing the distance from the edge of the CLT panel to the axis of the rods improves furthermore its fire resistance. Hence, the position of the rods in the panel must be carefully chosen to achieve high efficiency and still keep the rods in the longitudinal layers of the panel.

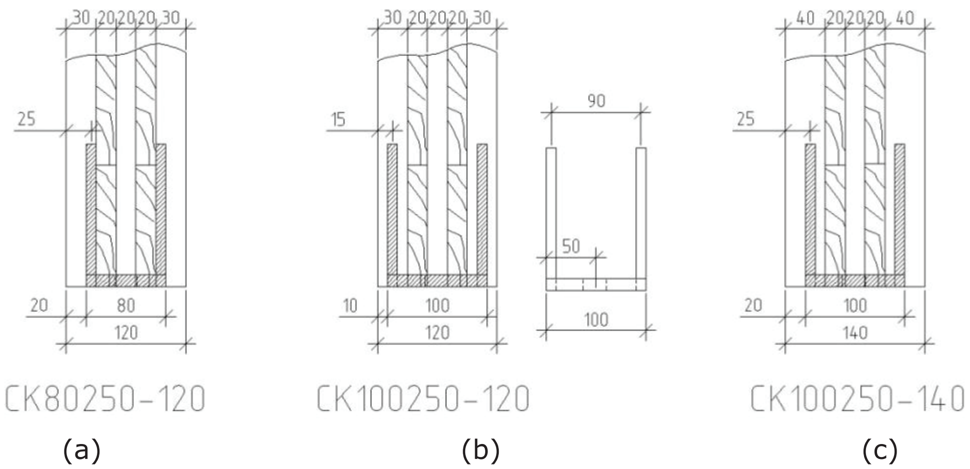
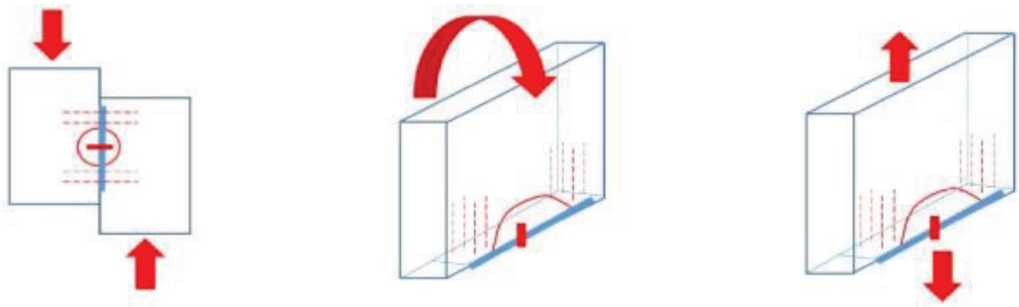


Figure 4 Configurations of connector depending from CLT panel thickness

The option of attaching the plate to the CLT panel with full-threaded screws is also possible as one of the variations of this type of connector. Particularly efficient and low compliance of the connection can be ensured by inclined screws in different directions. Inclined screws have low slip deformations and can be quickly installed in production without quality control of the connection, unlike glued-in steel rods. A connection with screws can be a second equivalent version of the developed system for connecting building frame panels, which is based on the same pitch of standardized connections along the edges of the CLT panel, DLT panels or GLT elements.

2.3 Experiments

To consider the variety of loading states acting on the connector, different tests have to be performed. An overview of the possible tests carried out in this project are shown in Figure 5.



(a) (b) (c)

Figure 5 Test configurations for the connector: shear (a), bending/torsion (b), pull-pull (c).

3 Analytical evaluation

3.1 Case study building

To analyse the magnitude of the forces that act on the connection under consideration of the various possible applications in the different locations of the building, a 3-story case study building (Figure 6) with plan parameters of 6 · 12 m and a height of 9 m was modelled. The building has openings in the walls in the form of doors and windows. There is no rigid core in the form of a reinforced concrete staircase or similar. The rigidity of the structure is ensured by the connection of longitudinal and transverse walls, as well as by fastening the walls to the ceiling. To model the new type connector with glued-in rods, which is located along the longitudinal sides of the panels with a spacing of 1 m and a distance from the corner of the CLT panels of 0.5 m, a rod type finite element was used. Along the height of the wall panel, two connectors were taken at the top and bottom at a distance of 400 mm from the edge and between each other. The connection between the panels is hinged. The load on the floors and roof was 4 kN/m^2 and the wind load on the walls of the building was chosen as 60 kg/m^2.

The thickness of the CLT panels in the walls was 100 mm (5·20mm each board) and 120 mm in the floor panels (2·30 mm outer layers of boards, 3·20 mm internal layers).

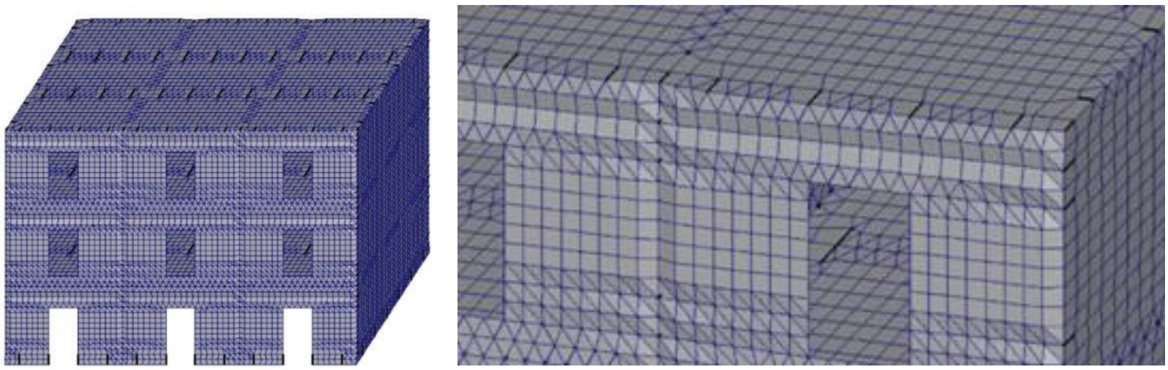


Figure 6 General overview and detail of the modelled case study building.

The model is made using plate elements measuring 0.5 · 0.5 m. To obtain the forces M, Q, N in the nodes, the rod-type finite elements for the connectors was used.

4 Results and discussion

4.1 Experiments

A first test series has been carried out at Tallinn University of Technology. The typical failure pattern of a test in pull-pull configuration is shown in Figure 7.

The failure is characterized by bending of the steel plate and pull-out of the rods. The basic pull-out failure of the rods is brittle due to the rather short glued-in length, however, the steel plate is sufficiently slender to provide ductility in the connection.

Figure 7 Failure pattern of the pull-pull test.

The load-deformation behaviour of the connection is shown in Figure 8. It can be seen that after a first linear elastic behaviour, yielding occurs in the steel plate at the location of the center bolt. Failure occurs through pull-out and splitting at the inside row of the rods.

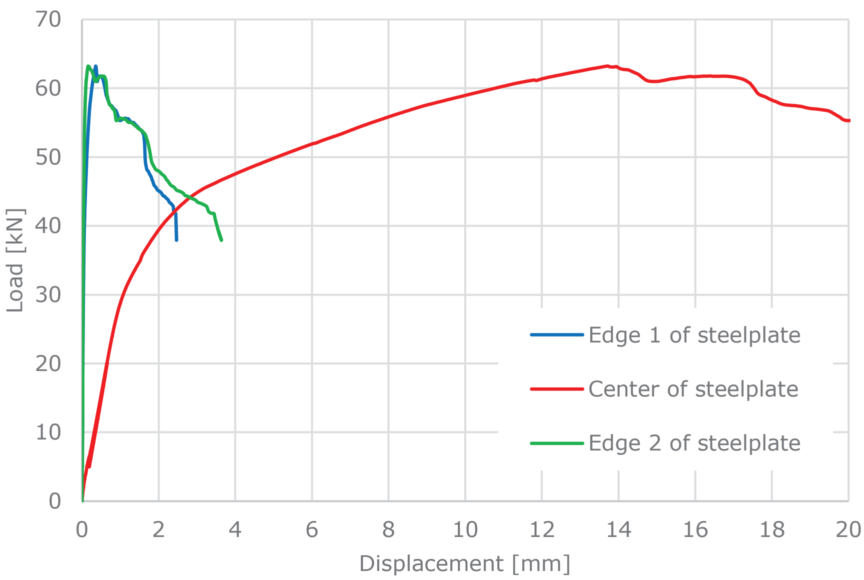
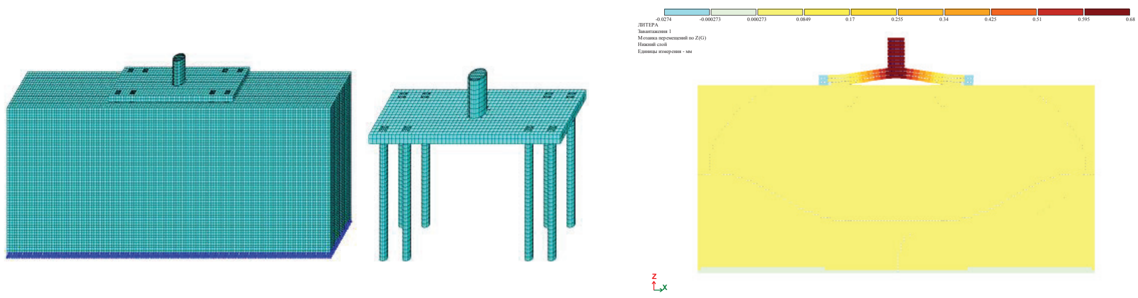


Figure 8 Load-deformation behaviour of the connection in pull-pull configuration.

Taking into account the magnitude of the load-bearing capacity of the connection and the magnitude of the forces in the connection, the modelling and analysis of the deformation and compliance of a 12 mm thick metal plate (Figure 9 a) were performed. The plate deformations were determined under loading of 20 kN, 30 kN, 40 kN and 50 kN. The corresponding elastic deformation in the middle of plate are 0,282 mm, 0,408 mm, 0,544 mm and 0,68 mm (see Figure 9 b), respectively.



(a) Geometry of the FE model (b) Deformation at 50kN load

Figure 9 FEM modelling of the connector (a) and steel plate deformation (b).

Up to the load level of 40 kN experimental and calculating data are linear. The onset of yielding is important for the next steps of optimisation of the connector. One possible way to decrease the plate deformation is reducing the distance between the rows of glued-in rods from the center bolt. However, the elastic deformation of steel plate of 2-3 mm at loads around 50 kN is much better compared to that of simple dowel-type connections. A possible alternative to this connector can be the use of inclined screws instead of glued- in rods in order to reduce the deformation in shear.

4.2 Discussion

The preliminary calculations of the FE-model of the 3-storey case-study building with the proposed connector with glued-in rods (Figure 10) show that the resulting forces in the connections do not exceed the estimated theoretical values of load-carrying capacity derived from the standards in pull-out and shear loading (Table 1). The performance is ensured for all components and connections. Further static tests on the connectors under different loading conditions (see Figure 5) will be carried out to verify the expected strength and stiffness parameters and to identify the failure mode.

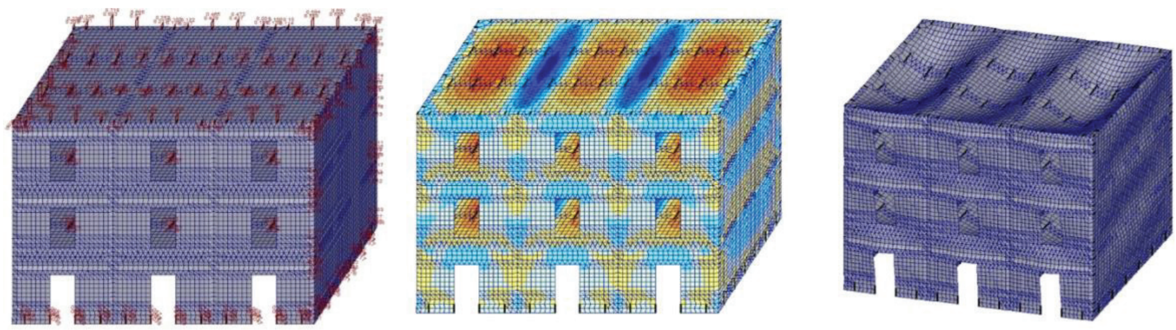
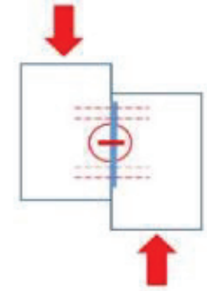
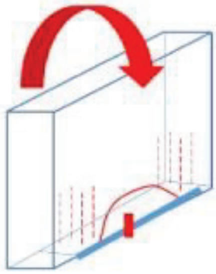
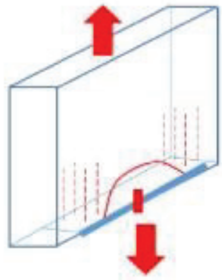


Figure 10 Results of calculation buildings model

According to EOTA TR 070 (EOTA 2019) for case «a) shear» the determination of the lateral load-carrying capacity of the glued-in steel rods the design provisions specified for laterally loaded dowel-type fasteners in acted EN 1995-1-1.

According to SNiP II 25-80 (SNiP 1980), the pull-out and punching (compression) strength of glued rods is considered to be the same, which means that one row of glued-in rods (or 4 rods in each connector) will be sufficient in a bending connection.

Table 1 Predicted and calculated values of the connector strength.

	Shear	Bending/rotation	Pull-pull
			
Predicted capacities	Q =27,4 kN (8 rods as dowels) = 92,8 kN (8 rods M10) = 49 kN (bolt M20, 5.8)		N = 46,5 kN (rods) = 78,4 kN (bolt M20, 5.8)
Max. calculated forces in the case study building	Q = 14,8 kN	M=3,2 kNm	N = 20,2 kN

5 Conclusions

Connections with glued-in rods in CLT panels have already been studied by several researchers. Most of the research has be done on uniaxially loaded rods. However, the application of rods in practical applications requires also the evaluation of rods under complex loading situations with interaction of axial and lateral loads.

In this project, a new type of connection system with a steel plate and glued-in rods for CLT panels is investigated both analytically and experimentally. The proposed new type of connection system is universal, easy to implement in production and can be used (with minor modifications) in buildings of 5 floors and above. The glued-in rods can be replaced with screws if necessary. However, it should be considered that the costs of connections with glued-in rods is much cheaper in Ukraine than connections using fully threaded self-tapping screws.

The proposed geometry is suitable without modification for the case-study building with 3-5 floors, where the forces do not exceed the analytical and experimental resistances. For tall buildings in platform construction, when the load between the walls exceeds the crushing strength of the timber perpendicular to the grain of the floor panels, it is necessary to insert steel tubes between the connector plates that transfer the loads through the floor panel. This solution has been used already in many cases for the transfer of loads through floors between columns.

6 Acknowledgements

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Assessment of strength and stiffness properties of aged structural timber

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[3] Arro & Agasild Inseneribüroo OÜ

Summary

This paper investigates and compares available visual assessment methods and applies them to aged structural wood. To validate and find appropriate visual characteristics to determine the strength and stiffness of the timber elements, non-destructive and destructive four-point bending tests were performed. The results show that the grading standards significantly underestimate the real strength of the wood or, even more, reject the material as inappropriate for construction. Therefore, there is plenty to optimize for using old wood in structures.

Keywords: visual grading, in-situ assessment, aged structural timber

1. Introduction

It must undergo a grading process to determine the strength class of a new timber element. Visual grading involves an assessment by a grader who examines the key characteristics that can potentially reduce the strength of the sample and then designates the visual grade accordingly. The entire process is conducted according to established standards and is built on years of experience. However, when evaluating aged timber, we lack a standardized method to assess its quality. The matter is further complicated by the lack of data on old in-situ wood and its exploitation, which would help to evaluate its condition. Consequently, there is a real practical need to assess the condition of old timber to avoid unnecessary demolition and the loss of valuable and structurally sound building material.

2. Materials and methods

The material used for the tests originated from a building located on Vaksali street, Tartu. Despite the lack of historical information on the building, it can be assumed that the timber used in this investigation is about 120 years old. In this research, 19 samples in total divided into two groups were tested. 15 samples had a smaller cross-section (CS) of ~100x100 mm and four of them with a larger CS. All specimens were photographed, given a number, and each face was marked from A to D – see Figure 1. Visual grading according to the standards UNI 11119 [1], UNI 11035 [2], and INSTA 142 [3] was performed before mechanical tests. The non-destructive (ND) bending test according to EN 408 [4] was carried out on all four sides of the specimen, the destructive test being followed for the weakest side.

3. Results and discussion

Mechanical tests show that visual grading standards significantly underestimate the real strength of the wood – see Figure 2. Although the values closest to the test were obtained with INSTA 142 (for new wood), UNI 11119 standard provides the most suitable foundation for visually assessing old wood. The reason is the simplicity of the method and the possibility to evaluate partially hidden structural wood. Since UNI 11119 considers the most influential parameters, the results are like the results obtained with more thorough and time-consuming methods.

Figure 1 Marking of specimens

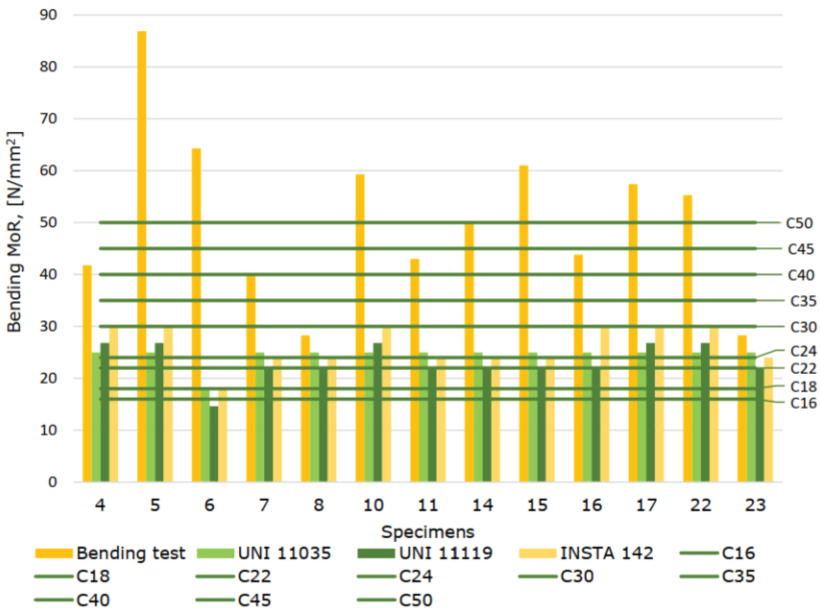

Figure 2 Comparison of test and visual grading results

4. Conclusions

Being on the safe side, the new timber sorting standard, INSTA 142, is limited to the strength class C30 and the Italian standards UNI 11119 and UNI 11035 to C24 accordingly. From the designer's point of view, such a limit is sufficient for safe design. Still, from the point of view of effective use of the material, further research is essential to take advantage of the best properties of the material that have endured for centuries.

5. References

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Bending and vibration behaviour of CLT-steel composite beams

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[1] Technische Hochschule Mittelhessen – University of Applied Sciences, Gießen, Germany

Summary

Strengthening of cross-laminated timber (CLT) by a composite effect with steel girders could expand the application of CLT ceilings to spans over 8 m. 4-point bending tests were carried out with different cross-sections for spans of 8.10 and 10.80 m. The composite effect increases the bending stiffness by about double compared to no composite. For a worthwhile composite effect, both materials should contribute a balanced share of the stiffness. For the same construction height, a larger CLT proportion resulted in a higher elastic load limit. All setups met at least the vibration standards of a frequency of 6 Hz.

Key words: Steel-Timber-Composite; Cross-Laminated Timber; Hybrid Structures; composite bending capacity; composite bending stiffness; vibration behaviour.

1. Introduction

Cross-Laminated Timber (CLT) is a sustainable construction type for ceilings. Strengthening of CLT by a composite effect with steel girders can widen the application. The composite effect leads to a higher load-bearing capacity for the same material consumption. The efficiency depends to a large extent on the load-bearing capacity and the flexibility of the shear connection. In previous studies, the load-bearing behaviour of inclined fully threaded screws and shear studs casted-in CLT-openings as shear connectors of CLT-steel-composite beams was investigated [1]. Based on this, large-scale laboratory tests were conducted to investigate the bending behaviour of CLT-steel composite beams. This work presents the results of the reached composite bending load-bearing capacity and the vibration behaviour for application scenarios of spans between 8 and 11 m.

2. Methods

The aim of the investigations was to determine the elastic bending stress limit and the bending stiffness of the CLT-steel composite beam considering the flexibility of the shear connectors and the low rolling shear stiffness of the CLT. Two different cross-section setups (HEA200 + CLT200 L5s; HEA160 + CLT240 L7s) were investigated in 4-point bending tests, each with spans of 8.10 m and 10.80 m. In all setups, fully threaded screws were used as shear connectors. In one additional setup, shear studs were used as a comparison. Thereby, the vertical deflection and the horizontal slip were documented by path transducers and the strains by strain gages. Comparable experimental investigations have been carried out in [2] and [3]. The previous work is limited to shorter spans, thinner CLT with a maximum of five layers, other shear connectors and a smaller scope of testing. Thus, extensive work was needed to fully assess the load-bearing behaviour.

Since the applicability of timber ceiling structures depends on serviceability, additional vibration tests were performed by stimulating the composite beam with different impulses.

3. Results and discussion

The elastic bending stiffness of the test girders is about twice as high as the bending stiffness without any composite effect. The bending stiffness of the tests agrees with the values of the bending stiffness calculated back from the vibration tests, so that they confirm each other. In all tests, the elastic stress limit of the steel was first reached. Only after a plastic deformation of the steel, a failure of the CLT occurred. The shear connectors never led to a complete failure. For a worthwhile composite effect and the best possible use of resources, the ratio between the individual bending stiffnesses of the CLT and the steel girder must be optimised. A larger stiffness contribution of the CLT leads to a higher elastic load limit but increases the risk of a brittle failure. The investigated setups fulfil all deflection limits under a line load of 10 kN/m, which is realistic for office and industrial buildings in SLS, at a span of 8.10 m. For a span of 10.8 m, only lower limits are fulfilled unless the degree of composite is further increased, which would be easily possible. For spans of 8.10 m, a fundamental frequency of 10 Hz was determined for all setups and fulfils the more stringent vibration requirement of floor slabs according to Hamm and Richter [4] of 8 Hz. For larger spans of 10.80 m a fundamental frequency of 6 Hz was determined, meeting at least the minimum vibration requirements according to [4].

Figure 1 CLT-steel composite beam in 4-point bending test

4. Conclusions

The tests show that the achievable composite effect between CLT and steel is sufficient to efficiently achieve ceiling systems with spans between 8 and 11 m. The bending stiffness is doubled between the composite beam and a composite-free construction, although the shear connectors behave flexible. For the previously mentioned application scenarios, at least the minimum vibration requirements are already fulfilled by the composite beams. Further improvements can be achieved by an increased degree of composite.

5. Acknowledgements

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On-site application of end-grain bonded timber under low curing temperatures

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Summary

The end-grain bonding of timber components using the Timber Structures 3.0 technology (TS3) is an advancing construction method in timber engineering. This technology allows the realisation of any plate size by bonding plates on-site where low temperatures influence the performance. Therefore, investigations are underway to evaluate the influence of the low temperatures on the curing process. Additionally, research is in progress to discover techniques to reduce any adverse effects of low curing temperatures on the mechanical properties of the bond. The implementation of particular measures, such as the inclusion of milled heating wires into the joint and the pre-heating of the joint with a hot air blower, has been identified as advancing the potential for grouting even in the face of low external temperatures, as recent research has indicated.

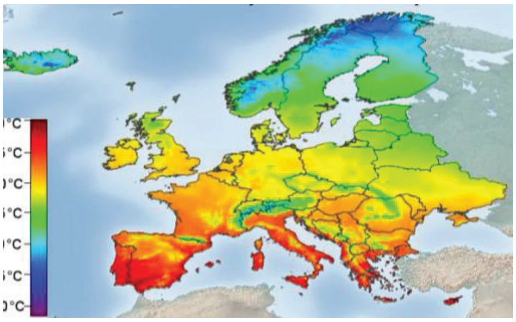
Key words: cross-laminated timber (CLT), flat-slabs, end-grain bonded timber, on-site application, temperature effect

1. Introduction

With the TS3 technology, timber components are bonded together in a statically load-bearing manner at the end grain surfaces. This offers the possibility of creating biaxial load-bearing flat slabs made of cross-laminated timber (CLT) in any geometry and size. The bonding takes place by filling a 4 mm gap with a casting resin without lateral pressure. A two-component polyurethane casting resin is used. However, to establish this technology internationally and thus provide a high-quality climate-neutral replacement for reinforced concrete slabs, the processing temperature of at least 17 °C specified by the casting resin manufacturer is currently still a challenge for the construction site application. The reason for this is that this temperature is hardly or only rarely reached in parts of the European sales market, especially in Scandinavia, but also in the Baltic States and Central Europe during the colder season of the year (see Figure 1, left). Accordingly, solutions must be found to extend the applicability geographically without being limited to one season.

2. Material and Methods

Previous studies have established that lower curing temperatures may negatively impact the mechanical properties of the end-grain bonding of timber components. Two potential compensation measures are under consideration to address this impact. The first approach incorporates a heating wire into the joint, allowing for precise temperature control, which guarantees effective bonding conditions at low ambient temperatures. Numerical simulations and experimental validations are carried out to investigate this approach. An alternative method involves utilising a hot air blower to direct warm air into the joint through the filling hole prior to the casting process. The aim of this application is to sufficiently preheat the joint, consequently elevating the surface temperature of the wood or pre-treatment and improving the bond between the pre-treatment and casting resin. This approach is investigated experimentally with the aid of temperature measurements. Spruce wood with a wood moisture content of approx. 12 % was used for all tests.



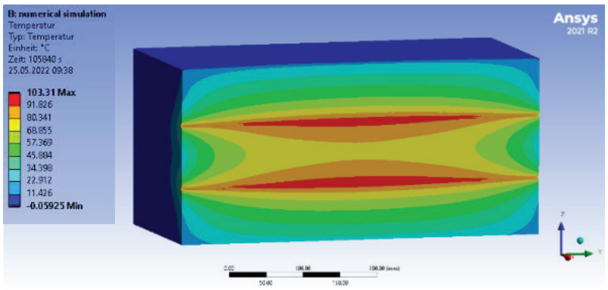


Figure 1 Average air temperature in Europe (left), source: https://www.wetter-atlas.de/klima/europa.php. Results of numerical analysis: Temperature distribution after 29 h (right).

3. Results and Discussion

Figure 1 (right) demonstrates the temperature distribution at the interface between the wood and casting resin. This is determined by a numerical simulation after 29 hours, at which stage a stable temperature distribution has been established. The visual representation uses a colour gradient to depict various temperatures, with red representing the highest temperatures and blue indicating the lowest. A clear temperature pattern is observable, with the heating wires showing the highest temperatures (reaching around 100 °C), while the outer surfaces record the lowest temperatures, consistent with the ambient temperature (0 °C). Vertically along the testing object, the temperature reduces gradually from the heating wires outward and to a lesser extent between them, with a temperature difference of approximately 20 Kelvin. Furthermore, there is a detectable reduction in temperature from the inside to the exterior of the test sample. After minor adjustments to the numerical simulation, this also agreed excellently with the experimental results, so that the simulation can be used to calculate the heating wire settings in future.

The tests with the hot air blower show, contrary to expectations, a distinct decrease in temperature during the blowing phase. After deactivation of the hot air dryer, all measuring points return to their original temperatures. One plausible assumption for the fact that the temperature does not rise as expected is that the air blown in, with limited heat storage capacity (≈ 1.005 kJ/kgK), cooled considerably during passage through the 30 cm-long filling hole, in close proximity to the cold wood, before reaching ambient temperature.

4. Conclusions

The Experiments utilising embedded heating wires show evidence establishing the efficacy of this technique in achieving the required curing temperature within the joint, even in low ambient temperatures. Additionally, tailored numerical simulations that assess temperature distribution over time across the cross section highly correlate with actual outcomes, demonstrating predictability. On the other hand, the second option being examined, which involves using a hot air blower, does not appear to offer a promising compensatory measure. This is because there is no significant effect resulting from this approach. The heating wire method is a feasible approach, despite the substantial extra workload associated with milling, installation, heating wire adjustment, and quality assurance.

5. Acknowledgements

The project is a collaboration of Timber Structures 3.0 AG, Schilliger Holz AG, Henkel & Cie. AG, ETH Zürich and BFH. Gratefully acknowledged by the authors is the intense cooperation among the partners of this project, as well as Innosuisse, which is funding the ongoing project to a greater part.

FORUM WOOD BUILDING BALTIC

PROCESS INNOVATION

Planning sustainability for timber construction projects - example of the Student residential quarter "Campus RO"
Lore Köster

Multi-criteria decision support tool for selection of biobased facade materials
Veronika Kotradyová, Anna Sandak, Jakub Sandak, Gry Alfredsen

Revitalizing Modernist Districts: Neighbourhood Level Mass-Renovation with SOFTacademy project
Murel Truu, Lauri Lihtmaa, Mariliis Niinemägi

Airtightness and moisture behaviour of joints and VOC concentrations in wood and hybrid structures
Anti Rohumaa, Simo Erkko, Pertti Pasanen, Marko Hyttinen

Timber Reciprocal Frame Structures
Kertu Johanna Jõeste

Planning sustainability for timber construction projects - example of the Student residential quarter "Campus RO"

Lore Köster[1]

[1] Planungsbüro Köster, Stephanskirchen, Deutschlang

1. Project presentation

The student residential quarter at CAMPUS RO has the character of a lighthouse and sets new standards in many respects.
An open competition was held to find an urban planning and architectural concept that meets all of the client's criteria and expectations. A special living space has been created for the new generation of students in an architecturally, technically, digitally and sustainably optimized system.

Figure 1: (c) CampusRO Projektentwicklungs GmbH_bloomimages GmbH

1.1. Building and Usage

Characteristic values
Plot 8.500m²
Gross floor area (BGF): 6.500m² + 2.800m²
Living area: 4.500m² + 1.600m²

Structure of the building
Access via arcades
Wooden hybrid construction with Wood concrete composite ceilings
No basement, crawl floors für technical access
Parking spaces above ground

Usage
211 places of residence für students
Apartment Types: 11 x 4-room; 2 x 3-room; 161 x 1-room, 4 wheelchair accessible
40 serviced Apartments – of which 3 barrier-free/ 1 wheelchair accessible
4 roof terraces for the students/ 1 rooftop Bar for the boarding house
Common rooms: Multifunctional room, Fitness room, Campus Lounge, Wash lounge and bicycle workshop

1.2. Construction

Exterior walls: Timber frame construction (F30-B)
Exterior walls load-bearing: cross laminated timber (F60-B)
Inner walls load-bearing: cross laminated timber – every2nd axes
Ceiling and flat roof: wood-concrete composite with local concrete
Span over 2 axes = 6,40m
Bathrooms OG: prefabricated wet cells
Arcades: precast concrete elements

1.3. Energy Concept

Efficient building shell
- Timber construction in Passive house standard
- airtight building shell
- Detailed thermal bridge calculation

Photovoltaic system
- power 175 kWp
- Battery storage 233kWh

Decentral Ventilation
- Supply and exhaust air system, one ventilation unit per unit
- Visualization of Electricity consumption and generation

Heat supply
- District heating of Stadtwerke Rosenheim
- underfloor heating
- Fresh water stations per 2 units

2. Digital Model

2.1. Customer information model and BIM development plan

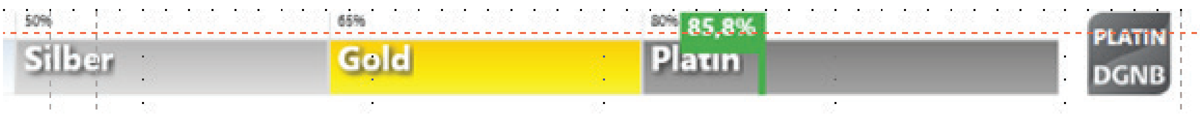
- Assignment of a BIM manager with the development of the AIAs and the BAP
- Obligation of the architects and specialist planners

2.2. Open BIM Modell

Creation of a digital model in ifc-format by the architects and specialist planners

3. Sustainability

DGNB-Certification (German Association for Sustainability) **in Platin**



Multi-criteria decision support tool for selection of biobased facade materials

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Summary

The paper summarises results from interdisciplinary studies (namely from environmental and social psychology, cognitive neuropsychology, cultural studies), dealing with decision process related to selection of a cladding material. The results from the literature review are put into "interaction" with studies dealing with LCC analyses and customized software for testing user preferences. Such analysis created a more complex understanding of the decision-making process. Further, conscious and unconscious factors were introduced in a decision (preference) process scheme. The "conflict" between the conscious and unconscious factors are addressed in the experimental part of research.

Key words: Decision making; Facade; Cladding; Emotions; life cycle costing (LCC)

1. Introduction

The tendency for development of sustainable structures and increasing environmental consciousness leads to reactivation of bio-architecture and use of biomaterials as an alternative for renovation and retrofitting of existing building façades. Façade is the first exposure line protecting buildings against environmental agents. Consequently, it has an important role related to the energy performance and interior functionality of a building. However, it has also impact to quality of urban and rural landscape, public space and human and community behaviour. In the case of bio-based materials, the awareness of weathering processes is indispensable for an honest presentation of information to the client. Another essential factor is maintenance and renovation schedule that are triggered after reaching "aesthetical limit state". Crucial information on how the building will look in the future, how often it would need to be maintained, and how much it will cost are necessary to gain credibility in the eyes of the client. The goal of this research was to compare the intuitive/unconscious decision regarding materials selection with judgment after introducing insights related to life cycle costing analyses.

2. Methods

This research includes a systematic literature research of 30 studies dealing with the decision-making process from psychology, neurosciences and social sciences perspective enriched with theory and practice behind the LCC analyses or other economical profile of selected wood and other standard building materials for comparison. A multimedia questionnaire including latest knowledge and integrating new technologies for interacting with respondents that was designed for additional targeted feedback implementing different strategies for user interaction and presentation of aesthetic-related images of building facades along the service life. The questionnaire was presented to the test set of more than 200 participants representing different countries, genders and wood-related technical comprehension. The hypothesis was that the respondents change their opinion after familiarizing with economic issues (investment cost, maintenance frequency) and after possessing supplementary information regarding environmental impact and related with it environmental awareness (local/imported resources or natural/modified wood).

3. Results and discussion

Customers perceive products characteristic through the sensory modalities, that are closely connected to material properties. Hence, visual, tactile and olfactory stimuli play a major role in a case of wood. Emotions play a crucial role by decision making. The research on emotions and decision making, reveals that emotions constitute potent, pervasive, predictable, sometimes harmful and occasionally beneficial drivers of decision making. At the same time economic factors, calculation of the operational and maintenance costs influences the final decision as well. The choice of wood as an aesthetically/emotionally appealing material or its artificial imitations, that are often used for claddings with an aim to create a friendlier appearance of a building and to improve the likeliness of the façade. In fact, bio-based materials give an impression of being suitable for any context, even if they have different forms or patterns. At the same time, the importance of informing the users about the operational costs is indispensable for the rational approach to materials selection. Conscious and unconscious factors are in permanent interaction. The study analysed and summarised factors that are influencing the decision process by choice of the cladding material, into two categories unconscious and conscious. Unconscious factors include subjective preferences (based on the personal history), environmental sensitivity, source and flow of information and cultural background, which is defined in literature as they are responsible for generation of decisions and the causation of behaviour. Conscious factors include economic benefits (initial, inspection, maintenance, replacement costs), environmental awareness, nationality (dependence on national legislation), materials characteristics (e.g., durability, appearance), required maintenance, materials availability, handling and storage, building location and climate, guarantee and support after purchase and finally trends and fashion. Further, the study also reflects on differences in decision process in private and public building sector. The hypothesis that the choices were changed after familiarizing with economic issues and/or after possessing supplementary information regarding environmental impact, was confirmed. However, the change of choice varied due to differences in psychographic characteristic of respondents and their subjective experience, cultural background as well as educational/experience related to wood.

4. Conclusions

Decision making is a complex process, driven by emotions. If the economic calculations are available, they influence the decision result. The success of the bio-based façade campaign depends on the trustworthy presentation of the advantages and disadvantages of these materials. Main issues that need to be considered when successfully designing building include material choice, that should always be knowledge-based and supported by honest feedback information from the constructor and investor. The selection of the specific bio-based product should be accompanied by the development of realistic maintenance schemes based on the experience of using specific solutions. Furthermore, the implementation of different materials and additional treatment processes should always be adapted to meet certain environmental and climatic conditions.

5. Acknowledgements

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Revitalizing Modernist Districts: Neighbourhood Level Mass-Renovation with SOFTacademy project

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Summary

This article discusses the neighbourhood-level renovation potential in Tallinn's modernist privately owned apartment blocks, with the aim of addressing the global need for deep renovation. The analysis considers international directives, national policies and municipal objectives, highlighting the focus of current renovation initiatives on apartment buildings. The discourse drives the ongoing conflict between energy-focused renovation and the preservation of spatial quality, especially in countries that favour partial renovation over the complete transformation of a building. It analyses the emerging impact of the new European Bauhaus (NEB) initiative, emphasizing the need to balance technical energy investments with cultural and aesthetic considerations.

Shifting the focus to Tallinn, the article deals with the challenges of modernist mass production housing districts, recognizing their technical structure, current decay and socio-economic limitations. Practical considerations for the transformation of Tallinn districts are discussed, including spatial regulations, the complexity of ownership and the different perspectives of apartment owners. As a solution, the SOFTacademy approach is introduced, proposing a collaborative model for renovation of buildings and outdoor spaces using prefabricated elements. The article outlines a 10-step process for neighbourhood-level renovations, emphasizing the importance of consulting with owners, creating blueprints, and entering into cooperative agreements.

The results show SOFTacademy's approach, which aims to achieve NEB transformation in the context of Mustamäe. The Tallinn Renovation Accelerator Service (TRAS) is presented as an important component that includes software solutions such as design criteria, the Renovation Strategy Tool (RESTO) and a facilitating system for configuring neighbourhoods at the community level. The article concludes by emphasizing the need for innovative models and software solutions to overcome barriers and facilitate the metamorphosis of monofunctional neighbourhoods into dynamic and attractive spaces, placing SOFTacademy and TRAS as central tools in this transformative journey.

Keywords: Neighbourhood renovation; Apartment buildings; Renovation Wave; New European Bauhaus; Prefabricated serial renovation.

Methods

The New European Bauhaus Compass serves as a guide for the development of New European Bauhaus projects, providing the basis for more in-depth assessment tools. It articulates the three core values of the initiative and outlines the trajectory for a project (Figure 1). Combining the NEW principles to concurrent renovation strategy we expect to trigger the neighbourhood-based renovations in residential districts.

Figure 1 New European Bauhaus (NEB) compass values

The expected impact by combining NEB with neighbourhood-based renovation strategy are as follows:

- **Larger volume** is more attractive for large companies that are currently focused on the new builds.
- **Scale effect** means reduced costs as construction companies can work with larger volumes through procurement.
- **Efficient site management** can minimize disturbance and thus results in a reduced environmental footprint.
- **Collective action** would increase social capital of the community by offering opportunity to reconsider and improve the function and design of semi-public spaces in co-creative manner.

Concurrent renovation of multiple buildings offers unique potential to reinvent the district. Neighbourhood-based renovation requires the stronger involvement of urban planners, architects and landscape architects. Not only can they contribute to the architectural design of buildings, but moreover enhance the spaces between them and assist in solving the challenges related to improved urban living.

Conclusions

It is evident that carbon neutrality in buildings requires much larger intensity of renovations to deliver climate targets. This renders the energy policy as driving force for buildings sector. Mass-renovation of such buildings that were one mass-constructed seems rational and promises the intensity needed. Combining energy targets with aspirations for spatial quality in renovations could be the key to modernizing outdated monofunctional residential estates that are in urgent need of upgrades. Urban transformations, especially in neighbourhoods where residents have a significant stake, require a comprehensive, multi-scale approach to understanding the social-ecological-technological and local governments, the private sector, and civil society. However, individual private citizens still occupy a central role in the decision-making process.

To effectively organize neighbourhood revitalization, a comprehensive suite of software is essential. This should include various tools, beginning with decision support tools that assist private owners in assessing the cost-to-benefit ratio, as well as evidence-informed policies and reprogrammed incentives at the municipal level. Lastly, a landscaping catalogue for apartment associations is necessary to aid private owners in implementing solutions that align with biodiversity and climate adaptation goals.

Acknowledgements

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Airtightness and moisture behaviour of joints and VOC concentrations in wood and hybrid structures

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Abstract

The joints of the building elements are the weakest link in the air and vapor tightness of the building envelop, as in some cases they form a very complex point of discontinuity in the air and vapor barrier layer of the building envelop.

The aim of this study is to produce information about sustainable and economical structural, jointing, and sealing solutions. A two-story test building was designed and built for empirical field research. This publication will present the connection and element solutions of the test building, in addition to outlining the research methods employed in the study. The main objective of the test building is to monitor how different seasons and extreme conditions impact the performance of the structures and joints, as well as the quality of indoor air.

Key words: Building envelop; Airtightness; Field research; Jointing and sealing, VOC.

1. Introduction

Buildings have a significant impact on energy consumption, as the energy use of buildings alone is about 40 percent of Finland's energy consumption. Buildings and indoor air quality are also of great importance to people's health, as people spend most of their time indoors. Achieving and maintaining a high level of airtightness of a building envelop is essential for energy efficiency, occupant comfort, and indoor air quality. The airtightness of a building envelope, which prevents uncontrolled air leakage, is influenced by several factors e.g. the quality of construction, choice of materials, windows and doors, insulation, moisture barriers, climate and environmental conditions. At the same time, the airtightness of the joints of the elements used in construction plays an important role in both the energy efficiency of the building and the air quality of the indoor environment. Local moisture convection through the building envelope can cause serious moisture damage to structures (Annila et al., 2017) and affect indoor air quality (Mendell et al., 2018). There are several studies available in the literature on the airtightness of buildings and related measurement techniques (Prignon & Van Moeseke, 2017). Air tightness has been studied both in laboratory experiments and with the help of various simulations and models (Jokisalo et al., 2009; Kalamees & Kurnitski, 2010). Although most of these studies claim that simulations correlate well with actual measurement results, some parameters such as work quality and environmental conditions are still difficult to model (Prignon & Van Moeseke, 2017). In addition, more empirical field research is needed to improve and complement existing models.

The airtightness of buildings has also been investigated with field tests, where the influencing factors have been the construction methods and insulation materials of wooden frame houses, the insulation materials of log houses and the roof structures of buildings. The study concluded that the average air-tightness values do not meet the air-tightness level recommended in Finland, but nevertheless, good airtightness of individual houses was achieved in all house groups, regardless of the structure, floors, ventilation system or construction technology (Vinha et al., 2015). However, the results suggest that further studies on the airtightness of buildings and the factors affecting it are needed in the future as well.

In order to understand the effect of different factors on airtightness and to improve existing models and simulation programs, it is important to conduct field studies with real tolerances and materials. At the same time, it is very difficult to conduct well-controlled field studies in buildings that are in use. In these buildings, it is possible to monitor changes during use, but changing different conditions and simulating parameters is often almost impossible.

The building's air quality is also affected by volatile organic compounds (VOCs). The concentrations of VOCs inside a building are notably affected by the selection of building materials, particularly wood. The emission of VOCs from wood structures can vary depending on factors like the wood species, surface treatments, and environmental conditions. Terpenes are the most emitted VOCs from wood materials.

The primary objective of this study is to establish a research platform in the Savonlinna Technology Park. We will investigate the airtightness and moisture behaviour of various timber and hybrid structures under real-world field conditions. Furthermore, we aim to simulate a range of extreme conditions and closely monitor indoor air quality, including VOC emissions, both during the construction and operation phases.

2. Methods

2.1. Test building

As part of the project, a 2-story test building is built and will be equipped with genuine industrial materials, joints, and tolerances.

Figure 1 A test building built in Savonlinna

For industrial wood construction, the functionality of critical connection and material solutions is demonstrated on an outdoor research platform. The main objective of the research is to investigate the air and vapor tightness of the building envelope and understand how moisture behaviour in wood structures affects the performance of structural connections. An individual mechanical ventilation system with automated control is installed on each floor of the test building to create the required conditions within the building.

The lower, intermediate, and upper floor elements of the test building are made from CLT (Cross-Laminated Timber) panels. The exterior walls of the first floor are constructed from LVL (Laminated Veneer Lumber) and LVL-concrete hybrid sandwich elements, equipped with sensors during manufacturing to monitor the hygrothermal behaviour of the elements. The second-floor exterior wall elements are constructed from CLT panels. The roof structure is built using LVL panels and beams on top of the load-bearing CLT frame. The test building is equipped with 14 windows and two doors. Various sealing and insulation solutions have been used in the test building, and their performance will be monitored over the years.

2.2. Sensors used in the test building

The test building is equipped with modern sensors and data collection systems installed inside structures and elements. In monitoring the functionality of the structures, e.g. thermal imaging technology is used.

Table 1 Sensors used in the test building.

Sensor	Parameters to be measured	Quantity (pcs)
IOTSU® L3 DP01	Pressure difference	10
IOTSU® Rugged AQ09	PM2.5 and PM10, CO2, TVOC, temperature, humidity.	3
Elsys ELT-2-HP	Built-in sensors for measuring temperature and relative humidity.	12
Elsys EMS	Sensor for measuring door position, temperature, humidity and acceleration.	3
Milesight AM319 HCHO	The device measures temperature, humidity, lighting, air pressure, as well as the amount of carbon dioxide, formaldehyde and additional compounds (TVOC) and small particles and detects movement with a PIR sensor.	1
Milesight EM300-TH	Weatherproof temperature and humidity meter	1
Wiiste SH1	concrete moisture and temperature measurement	10
Wiiste WM1-WAN	Wood moisture meter	5
3K factory sensors	RH and temperature	160

The sensors used in the test building can be broadly divided into three levels, of which the first level consists of the temperature (T) and humidity (RH) measurement sensors (160 pcs) manufactured at the 3K electronics factory of South-Eastern Finland University of Applied Sciences. The second level consists of commercial LoRaWAN (Low Power Wide Area Networking) remotely readable sensors. The third level consists of new and under-development sensor solutions, which will be installed in the test building during its use.

2.3. Airtightness measurements

A building's envelope airtightness is a significant factor for the functional performance of structures, energy efficiency, and indoor air quality. A characteristic value can be determined for the building's airtightness, which is the air leakage rate at 50 Pascals pressure difference per unit envelope area, known as q50 ($m^3/(h\ m^2)$).

For new buildings, the regulation requirement for airtightness is 4.0 m³/(h m²), which can only be deviated from when usage or structural solutions demand it. Well-designed and executed buildings typically have air leakage rates significantly below this requirement. An excellent air leakage rate is 0.6 m³/(h m²) or lower, which is a typical value for passive houses.

The building's air leakage rate is determined according to standard SFS-EN ISO 9972:2015 at a 50 Pa pressure difference concerning outdoor air. In the method, all the openings in the building envelope are tightly closed during the measurement, such as outdoor and exhaust air vents, drains, and chimneys. External doors and windows are closed during the measurement. The building envelope's air leakage rate q50 (m³/(h m²)) is calculated as the ratio of the air leakage flow (m³/h) determined at a 50 Pa pressure difference to the envelope area (m²) of the building. The envelope area includes external walls with openings as well as the upper and lower floors. This is how the building's air leakage rate is measured.

2.4. VOC measurements

Volatile organic compound (VOC) samples were collected from both floors at a single measurement point located in the middle of the room. The samples were collected using Tenax TA tubes and two types of pumps, the SKC Essential and SKC 3000. The sampling durations were 30 minutes when the ventilation system was turned off and 45 minutes when it was operating. The flow rate of the pumps was maintained between 120 and 150 ml/min.

The collected VOC samples were then analyzed using a gas chromatograph (Agilent 7890) equipped with a mass selective detector (Agilent 5975C) following thermal desorption (TD) with the Markes TD-100. The column used was HP-5MS, with a column length of 50 meters and a film thickness of 0.5 µm. Compound identification was based on retention times, standard compounds, and the GC-MS data library (NIST02.L).

The concentration of VOC samples was analyzed in accordance with the ISO 16000-6 standard. VOCs were quantified as toluene equivalents, a commonly used metric for total volatile organic compound (TVOC) measurements. This approach was also applied in single VOC quantifications when reference compounds were unavailable.

3. Results

The air tightness of the test building was measured using the Minneapolis Blower Door Systems (Blower door, 2014). The measurements were carried out according to standard SFS-EN 13829 and ISO 9972. The test pressure differences varied between 10 Pa and 60 Pa, steps 10 Pa. Air change rate (ACH50, n50) and air permeability (air leakage index, q50) at 50 Pa have obtained automatically from a commercial blower-door software. Air flow required to maintain pressure difference of 50 Pa was divided by the inner volume of the measured house, and air permeability of the walls was calculated.

The test building was completed in November 2023, and the first airtightness measurements were conducted. At the same time, the heating and ventilation system was activated. The measurements indicate that the airtightness on both floors is below the required value of 4.0 m³/(h m²). The air change rate (n50) and air permeability (q50) at 50 Pa for the first-floor in the test house were measured at 2.31 1/h and 1.32 m3/(h m2), respectively. In the second-floor of the test house, the n50 value was found to be 0.64 1/h, and the q50 value was 0.38 m3/(h m2).

The concentration of Volatile Organic Compounds (VOCs) within the test house is presented in Tables 2 and 3. These tables provide Total Volatile Organic Compound (TVOC) values and highlight the six most prominent compounds detected in test house.

Sample collection followed a chronological sequence and commenced with no ventilation or heating in operation.

Table 2. The environmental conditions, ventilation, TVOC concentration and the concentrations of the six most significant compounds in floor 1. The concentration of compounds is given in micrograms per cubic meter air (μg/m^3).

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Ventilation	off	off	off	on	on	on
Temperature (°C)	8	12	16	17	18	19
RH (%)	58	61	58	46	52	54
TVOC	738	677	1238	226	176	141
α-Pinene	307	220	477	54	47	37
β-pinene	29	22	46	5	4	4
3-carene	64	54	91	10	8	8
D-limonene	42	39	64	6	3	3
Hexanal	38	33	60	6	5	6
2-ethyl-1-hexanol	57	67	97	24	17	18

Table 3. The environmental conditions, ventilation, TVOC concentration and the concentrations of the six most significant compounds in floor 2. The concentration of compounds is given in micrograms per cubic meter air (μg/m^3).

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Ventilation	off	off	off	on	on	on
Temperature (°C)	10	12	16	17	19	19
RH (%)	65	57	56	49	49	51
TVOC	3569	1781	2696	365	239	271
α-Pinene	1999	858	1067	169	83	104
β-pinene	143	59	86	9	5	6
3-carene	481	262	399	44	29	32
D-limonene	124	74	140	9	5	6
Hexanal	120	61	122	10	7	9

2-ethyl-1-hexanol	114	97	166	28	21	21

The VOC emissions in the test building were primarily originated from the wooden flooring and wall materials used in the building. As a result, the air contained a significant number of terpenes derived from wood, such as alpha-pinene, 3-carene, and limonene, for instance. Terpenes are most common VOCs emitted from wood materials. Additionally, various adhesives and sealants used in the house also contributed to VOC emissions. VOC emissions decreased significantly when the ventilation system in the test building was activated. The environmental conditions also have an impact on the emissions of wood materials.

4. Conclusions

The project's primary focus is on investigating the airtightness and moisture behaviour of joints in wood and hybrid structures under field conditions. The test building incorporates a variety of wood and hybrid elements, including LVL (Laminated Veneer Lumber), CLT (Cross-Laminated Timber), and LVL concrete. The research facility will be actively used for research purposes for at least the next five years, during which data will be collected using a range of commercial sensors as well as sensors produced at Xamk's Electronics 3K factory.

The main objective of the test building is to monitor how different seasons and extreme conditions impact the performance of the structures and joints, as well as the quality of indoor air.

The test building, completed in November 2023, underwent its first airtightness measurements upon activation of the heating and ventilation system. Results showed that the airtightness on both floors falls below the required threshold of 4.0 $m^3/(h\ m^2)$.

Regarding volatile organic compounds (VOC) emissions, they predominantly originated from wooden flooring and wall materials used in the building. Terpenes, including alpha-pinene, 3-carene, and limonene, were identified as the most common VOCs emitted from wood materials.

5. Acknowledgements

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Timber Reciprocal Frame Structures

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Abstract

This article introduces experiments exploring the integration of architectural design with engineering and the curation of production and construction. The work is focused on timber reciprocal frame systems and sustainable innovation. The framework relies on material-based design, low-tech methods, and modularity/adaptability. Existing structures are analysed, leading to the synthesis of four novel planar reciprocal systems. Standard timber materials are used for affordability and local feasibility. The work emphasises the significance of exploring alternative construction methods for sustainable solutions and enriching architectural design.

Key words: Reciprocal Frame Structures, Architectural Design Process, Interdisciplinary Collaboration, System Design

1. Introduction

1.1 Reciprocal frames

Reciprocal frame structure is a system where each element supports the next one, creating a closed circle where forces are distributed among all elements. Reciprocal structures are non-hierarchical. It is impossible to determine a specific starting or ending point (Pugnale, Sassone 2014). In contrast, in a hierarchical structure, each element has a defined position, order, and distinct functions.

Reciprocal frames have been used in ceiling and roof construction, in bridge construction as well as in creation of small scale objects and furniture throughout history (Godthelp 2019). The earliest examples of reciprocal structures date back to Neolithic civilizations. To create shelters, beams were tied together at the top, forming a cone-shaped structure covered with wood or soil (Popovic Larsen 2008). Earlier examples of bridge construction date back to the Roman Empire and the Ming dynasty in China.

In medieval architecture of Europe, wood was a primary building material. As larger spaces emerged, there was a need to cover larger openings. Therefore, reciprocal frames and similar structures were used until the 20th century in situations where obtaining sufficiently long timber was challenging (Godthelp 2019). From the 20th century onwards, engineered laminated wood and plywood elements largely replaced reciprocal structures and similar solutions in architecture.

Several modern academic works explore reciprocal structures in the context of sustainability. Short elements allow experimentation with the use of salvaged timber (Ruan, Filz 2022) or the creation of modular lightweight structures (Clarke 2013). Computational methods significantly expand design process possibilities.

1.2 Conceptual base

The principles of sustainability must become integral parts of the architectural design process. Material-based design – conscious material usage and enabling its long-term use, is crucial. Form-driven design processes can cause communication errors between architects, engineers, and builders and inhibit innovation (Oxman 2010). Even if the later stages of the work process consider material properties and production capabilities, compromises are often made at the expense of design (Tuksam 2020). To avoid this, it is necessary to take into account both material and production constraints already during the design phase.

Considering the entire production and construction process, the energy expended on labour and transportation becomes significant. Using locally produced materials becomes

essential. The low-tech design addresses precisely this issue by simplifying both production and final usage (Emekci 2020).
Architect Marvin Bratke aptly states, "A building may be designed according to the principles of the circular economy, but if we cannot disassemble the finished building into parts, we cannot reuse it." (Puhkan 2022). Through the use of modular and adaptable systems, a building can have more than one life cycle.

2. Design process and principles

2.1 Interdisciplinary design process

The profession of "master-builder" remained largely unchanged from the times of Daidalos and Vitruvius until the Industrial Revolution. The rapid development of materials and technology favoured the separation of architecture and engineering disciplines (Popovic Larsen 2011).
According to Popovic Larsen, architects, engineers, and skilled workers/builders must contribute simultaneously to the project's development. For example, the concept of a constructive solution can play a critical role in the design process (Popovic Larsen 2011). Thus, architecture's form, construction, and execution become entangled (Popovic Larsen 2020).
Designing, manufacturing, and building a reciprocal structure strengthens interdisciplinary connections and know-how. As a result, a more fertile ground is created for finding innovative solutions in architecture, engineering, and the construction field.

2.2 Geometrical principles

Architects Pugnale, Parigi, and Sassone highlight principles applicable to all reciprocal systems, distinguishing them from other construction methods (Pugnale et al. 2011).
"In the world of construction, the application of the principle of reciprocity requires:
- *the presence of at least two elements allowing the generation of a certain forced interaction;*
- *that each element of the composition must support and be supported by another one;*
- *that every supported element must meet its support along the span and never in the vertices (in order to avoid the generation of a space grid with pin-joints). "*

Architect Popovic Larsen identifies essential parameters for designing regular reciprocal structures (Popovic Larsen 2008):
- *Number of beams*
- *Radius through the outer supports*
- *Radius through beam intersection points*
- *Vertical rise from the outer supports to the beam intersection points*
- *Vertical spacing of the centrelines of the beams at their intersection points*
- *Length of the beams on the slope*

Popovic Larsen categorises reciprocal structures into three categories (Popovic Larsen 2008). Single reciprocal frame units, where at least three beams form a closed circle, with each element supporting the next. This is the basic unit of reciprocal structures. Multiple reciprocal frame grids, where single units are connected through their perimeters. Complex reciprocal frames are formed by adding single units into each other.

2.3 Structural principles

Reciprocal frame structure can be viewed as a truss system of beam elements, where each beam behaves identically. Examining the performance of an individual beam allows for the application of the acquired insights across the entire structure (Kotnik, Kohlhammer 2011).
In the case of a point load, the magnitude of the transverse force acting on a beam is independent of the load application point. However, the bending moments in the beams are greatest at the point where the load is applied. To minimise the bending moment, it

is most optimal to position the beams as close as possible to the end points of the supporting beam.
The connections between elements in reciprocal structures primarily function through the pressure and friction, allowing techniques like notching or tying together instead of mechanical fasteners (Kotnik, Kohlhammer 2011). Rigid connections create torsional forces in reciprocal timber structures, to which timber is relatively weak.
The distinctive feature of a reciprocal structure is that loads are distributed relatively evenly among all elements. The non-hierarchical structure makes the system highly flexible in redistributing loads - in the case of a failure of a single beam, forces are redistributed internally among other elements. In terms of practical use, this behaviour is favourable because large deformations allow for the safe repair of the structure before complete failure.

3. Exemplary novel structures

To design four novel reciprocal systems, eight different existing reciprocal systems have been analysed. The analysis encompasses the structure's background/history, material usage, geometric solution of the structure, and the structural mechanics, both from the perspective of a single beam and the entire system.
The four created systems are planar multiple reciprocal frame grids. Perpendicular connections enable the application of low-tech construction methods. Planar structures can be integrated into the existing spatial framework that commonly consist of vertical and horizontal planes to maximise space volume.
The proposed systems fit into the local material framework. This means that they can be built from standard timber materials and allow for material reuse. The materials used in the systems are standard-sized timber boards, beams, and plywood. The connections between elements are solved through friction, bolted joints, and binding with a strap or rope.

3.1 Two-layer mesh

A planar structure consisting of bent elements is inspired by the project "ReciPlyDome" (Brancart et al. 2017) and Friedrich Zollinger's patented lamella system (Petrović et al. 2022). Instead of lamellas with the specific geometry, it is possible to create a similar structure from bending-active elements, allowing the use of untreated standard materials.

3.1.1 SYSTEM

The comprehensive system is a planar multiple frame grid. It can withstand loads coming from any direction and must be supported either from the perimeter or at the centre of the system. The system consists of single reciprocal units formed by four elements, which can be both rectangular and rhombic. Such single unit structures can be created with practically any number of beams.

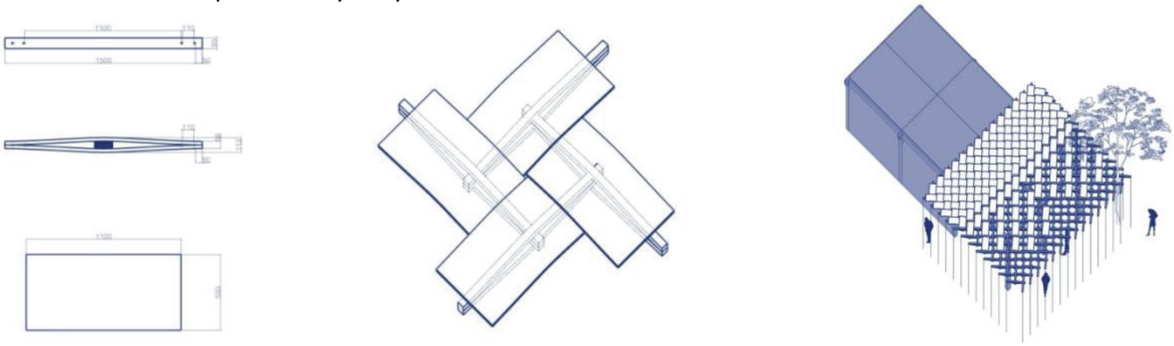

Figure 1. Two-layer mesh element parts, single unit, temporary roof structure.

3.1.2 ELEMENT

Two-layered bending-active elements support each other at their centre point. This causes the supporting element to have the maximum bending moment, but at the same time, it creates the largest cross-section in the centre of the element.
Unlike the plywood elements used in the "ReciPlyDome" project, the two-layered elements are made from standard-sized lumber to reduce the need for material processing. Mechanical fasteners are necessary at the ends of the elements to secure the two layers. Elements inside the system are compressed by other elements, and part of the tension on mechanical fasteners is relieved by the pressure and friction between the elements. Each element in the construction can be attached to a panel that creates a covering surface and acts as a stiffening layer.

3.1.3 MANUFACTURING

The preparation of elements can occur locally and does not require the use of industrial machines. The construction process of the system is somewhat time-consuming due to many elements and connections, but the light weight of the structure and the uniform logic of installing the elements are simplifying factors. The system needs to be assembled in element pairs during the building process. Two intersecting elements are placed between the layers of an element fastened with bolts at one end. The layers of the element are compressed at the other end and secured with bolts. This process is repeated for each element.

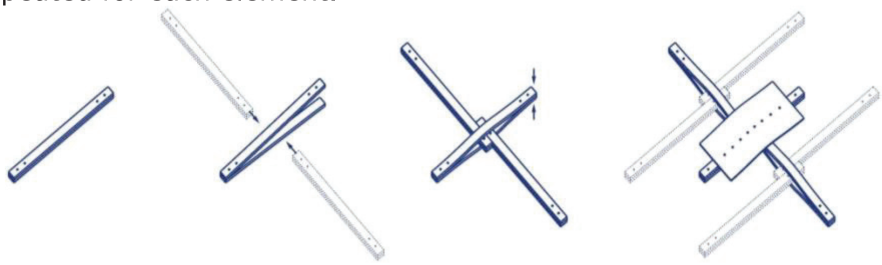

Figure 2. Assembly process of two-layer mesh elements.

3.1.4 PROTOTYPE

For the prototype, spruce boards with 28*95 mm cross-section measuring 1500 mm in length were employed. Due to the abundance of knots in spruce wood, it was imperative to choose boards of sufficient width to prevent them from breaking near the knots during the bending process.
The construction of the prototype served to demonstrate the feasibility of creating bending-active elements from timber boards. Additionally, it substantiated that the workflow is rapid and efficient, manageable even when conducted individually. The bending process of raw timber boards is the most time and energy consuming part of the assembly.

Figure 3. Two-layer mesh 1:1 prototype.

3.2 Three-layer weave

The planar system is inspired by the "ReciPlyDome" project (Brancart et al. 2017) and multi-layer element (Ruan, Filz 2022) solutions. Three layers have been used, with the upper layer being convex and the lower layer concave in relation to the global structure. The three-layer element system allows the formation of a planar structure from inclined elements. The scheme of mutual support of the elements is derived from the ceiling construction of the Seiwa Bunraku puppet theatre hall (Popovic Larsen 2008).

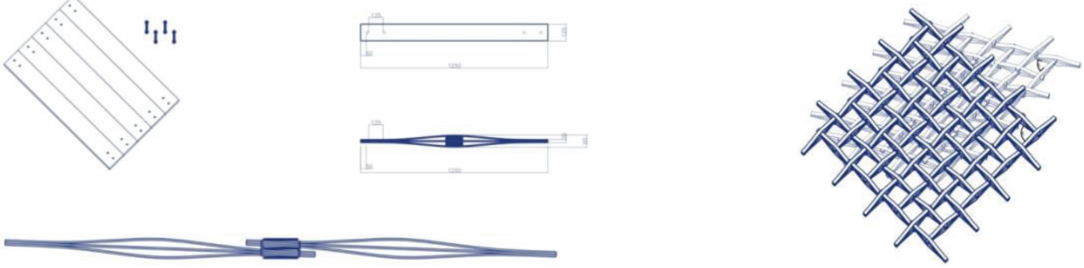

Figure 4. Three-layer weave element, inclined connection, structural system.

3.2.1 ELEMENT

Two intersecting elements are placed between the layers of the element. This ensures bending of the upper and lower layers, which, in turn, stiffens the entire structure. The ends of the elements aligned with the same direction can be connected. The flexible joint between intersecting elements allows the formation of both orthogonal and rhombic frames.

3.2.2 SYSTEM

The elements are arranged at an angle to the plane of a global structure. This intriguing geometry visually complements the bent element, creating a comprehensive system as if interwoven lattice. The geometry and structural performance of the system can be optimised by adjusting the lengths of the elements or changing the width and thickness of the material.

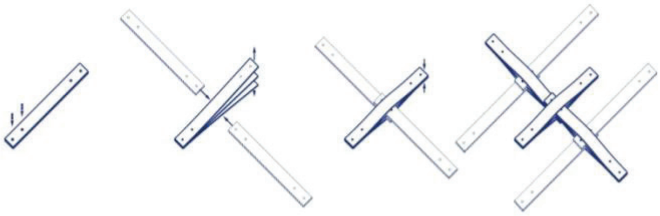

Figure 5. Assembly process of the three-layer weave elements.

3.2.3 MANUFACTURING

The elements are made from longitudinally cut strips of plywood, as the material must allow for significant bends. Therefore, the preparation is more time-consuming. The construction process is similar to the two-layer weave. The elements need to be added to the system in pairs, placing them between the layers of the intersecting element. The light weight of the elements and relatively short lengths allow for easy and low-energy transportation. Alternatively, elements can be produced locally. The three-layer weave consists of 125*1250mm plywood strips with a thickness of 10mm.

3.2.4 SCALE MODEL

Throughout the process of constructing the system, various materials were experimented with. Eventually, a decision was made in favour of plywood due to its considerable flexibility.
During the prototyping phase, it became evident that the selection of appropriate cross-sections and lengths is highly crucial. Over time, some of the plywood strips experienced

breakage, indicating that narrower or longer strips might have been more suitable for the plywood employed. The measurements of used plywood strips were 3*30*300 mm.

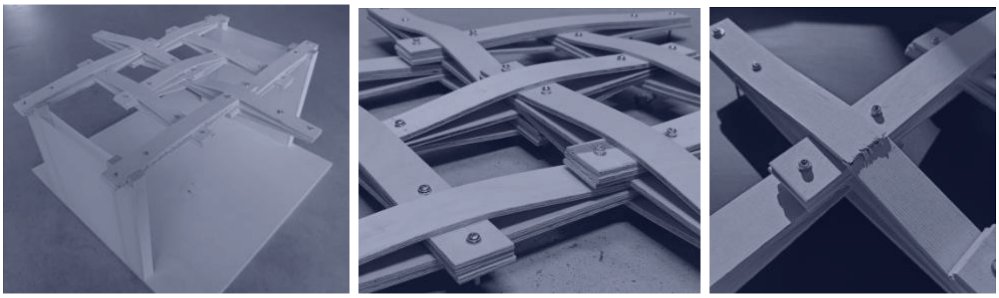

Figure 6. Scale model of three-layer weave structure.

3.3 Stiffened surface system

The system is inspired by the connection detail of the "Waste Wood Canopy" project (Browne et al. 2021) and the principles of a topologically interlocking flat-vault (Brocato et al. 2015). While most reciprocal frame structures involve reciprocity between beams on a single surface, this solution illustrates mutual support between multiple layers. In creating a stiffened surface system, the low-tech design and design-for-disassembly principles have been radically followed. The system can be a tool for tactical urbanism and community collaborations.

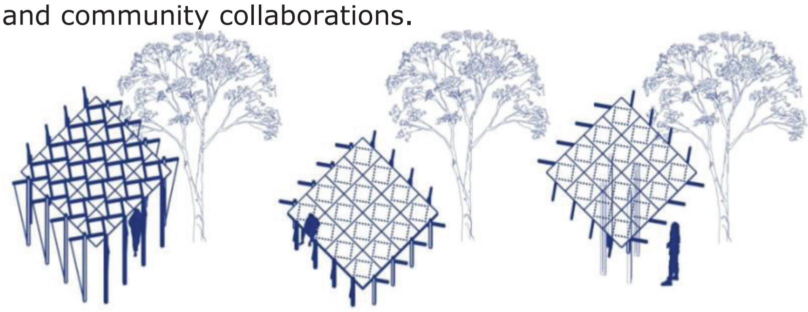

Figure 7. Three variations of the stiffened surface system.

3.3.1 ELEMENT

One element of the system is a single reciprocal frame unit consisting of four beams, connected by a sheet material detail placed on top, below, or both on top and below. Following the concept of design-for-disassembly, the sheets and beams are connected with a rope, as if sewn together. The load-bearing capacity of the element is relatively small, as it depends heavily on the strength of the sheet material. To increase the load-bearing capacity, all beams are turned at an angle to the plywood to ensure greater bending strength. Standard timber material can be used as beams, and plywood or CLT can be used as the sheet material. Alternatively, salvaged material can be used as beams.

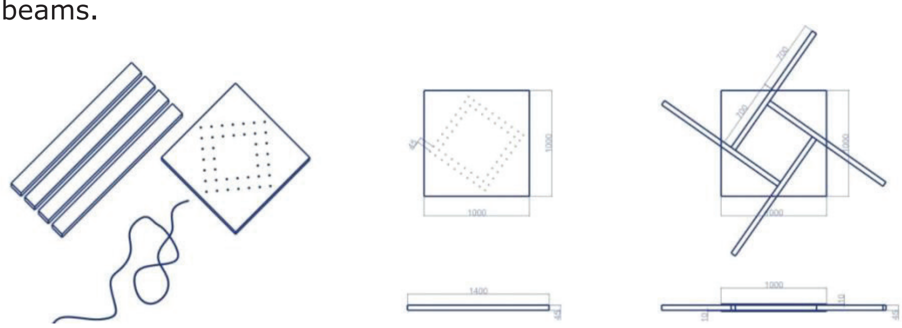

Figure 8. Single element of the stiffened surface system.

3.3.2 SYSTEM

The structural mechanics of the entire system depend on the geometry of the element. Elements of the system can be rearranged for solutions of different sizes and load-bearing capacities. The weakest structural solution is one in which plywood sheets are added only on top of the beams. This could be used, for example, in creating temporary canopies that are supported from the centre. The maximum load-bearing capacity is achieved when the sheet material is attached both below and above the beams - the bottom plate works in tension, and the sandwich solution prevents the beams from shifting away from each other. This can be used for creating terraces or roofs that bear larger loads.

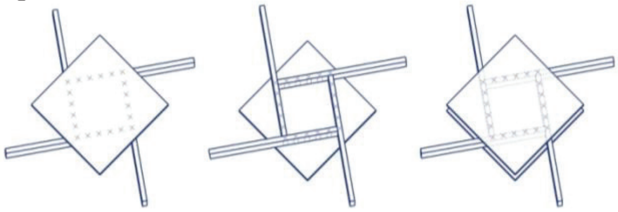

Figure 9. Element variations.

3.3.3 MANUFACTURING

Before the construction process, preparation is needed for the sheet material. The system can use standard-length wooden boards and beams, which do not require separate preparation. Plates and beams are connected by tying them together with a cord or rope. Creating crosses from the cords running over the top of the plate helps prevent the plate from bending perpendicular to the beam, thus ensuring greater strength of the system.

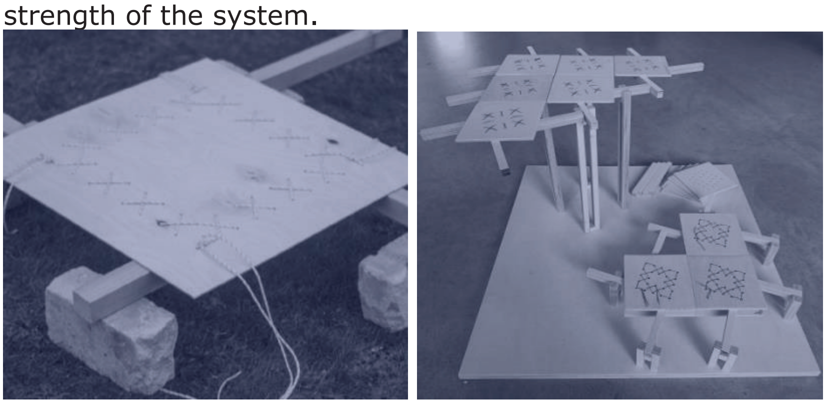

Figure 10. Prototype and scale model of the stiffened surface system.

3.3.4 PROTOTYPE

A 1:2 scale prototype consists of a 600*600 mm plywood sheet with a thickness of 3 mm and four beams with a cross-section of 45*45 mm. The beams are connected to the plate with a 5 mm diameter rope. Nine holes, spaced 45mm apart, are drilled on each side of the beam. Each beam is tied to the plate with a separate rope. Testing the prototype revealed that the load-bearing capacity of the element is smallest when the sheet material is on top of the beams and supports are in the perimeter. Placing the plywood below significantly increased the load-bearing capacity. A 3mm thick plywood sheet in this position was able to carry at least 60 kg. Under load, the element experienced a relatively large deflection, but no breakage occurred. To increase the strength of the element, it is possible to connect the beams to each other to form a separate load-bearing structure. Although such a solution would be structurally stronger, it would conceptually separate the plate material and the connection between the beams, serving only the purpose of forming the surface.

3.4 Spatially interlocking elements

The system of topologically interlocking elements is inspired by the flat-vault (Brocato et al. 2015), Sebastiano Serlio's ceiling construction (Pugnale, Sassone 2014), and the geometry of multilayered elements (Ruan, Filz 2022). The flat-vault system creates a continuous surface without the need for additional elements. The simple orthogonal truss geometry of Serlio's ceiling construction closely resembles the geometric scheme of the flat-vault. The interpretation of elements as multilayered allows the use of standard timber with a smaller cross-section.

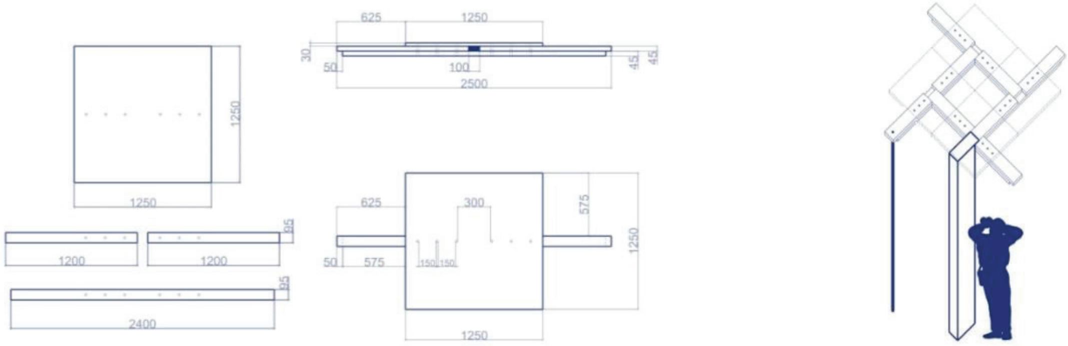

Figure 11. Single element of spatially interlocking system and support method.

3.4.1 ELEMENT

Each element consists of two standard-sized timber boards and one panel, creating a so-called three-layered element. The timber boards form two lower layers of the element and extend from under the plate to support adjacent elements. The logic of the topologically interlocking element dictates that every other element is rotated by 90°, and thus the elements support each other on their sides. Additional support points for the two-layered timber boards are at the intersection of the elements' centres, similar to the scheme of Serlio's ceiling construction. The purpose of it is to simplify the assembly.

3.4.2 SYSTEM

The unique feature of the system is its method of support. The integral system operates similarly to a flat vault. One of the principles of a flat vault is that elements on the perimeter must be supported in the same way as those supported inside the system. Elements on the perimeter must be supported alternately from below and above. Elements requiring support from below can lean on posts or panels; elements requiring support from above can be connected to the ground, for example, by a tensioned rope. The system is flexible and allows improvement in structural performance, for example, by locally increasing cross-sections and optimising parameters according to available material dimensions.

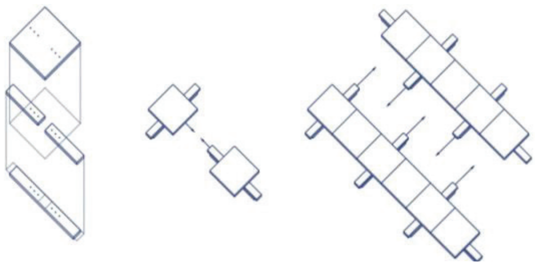

Figure 12. Assembly of spatially interlocking system.

3.4.3 MANUFACTURING

An element consists of two equally long timber boards and a plywood or CLT panel. One timber board needs to be cut in half - it becomes the central layer of the element, forming a mortise-like opening in the centre of the element. The three layers are fastened together with bolts. The construction and disassembly of the system are very fast since mechanical fasteners are not needed. The elements are connected by sliding them together, and they are added to the construction one row at a time.

3.4.4 PROTOTYPE

The first prototype consists of an 8*400*400 mm plywood sheet and two 21*45*750mm timber boards. Based on this, dimensions for a 1:1 scale prototype have been derived. The 1:1 scale prototype consists of a standard-sized 1250*1250mm plywood sheet with

a thickness of 16mm and standard-length of 2400mm timber boards with a cross-section of 28*95mm. The prototype comprises four identical elements. One edge of each element is supported by a post at the perimeter of the system, and the other edge is tensioned with a load strap to a weight on the ground.
The preparation of the four elements for the 1:1 prototype took about an hour for one person. Assembly and installation of supports took only a few minutes for four people. The prototype proves that the system can be quickly produced and assembled using low-tech methods. It also demonstrates that the method of perimeter support for the system works. The load-bearing capacity of the prototype is as expected, but for a more homogeneous result, a much thicker plywood sheet or CLT panel should be used.

Figure 13. 1:1 prototype of spatially interlocking system.

4. Conclusion

The article introduces four novel timber reciprocal frame systems. As opposed to more commonly used vault or dome structure, all of the proposed systems are planar in order to fit into the built environment. Architectural and structural properties have been considered and embedded into the design.
An exploratory approach is undertaken, employing a reciprocal support based design process that integrates architectural and engineering thinking from the outset, along with the curation of fabrication processes. Both the design process and the envisioned systems are situated within a sustainable framework.
The created models and prototypes serve as evidence that systems constructed based on theoretical knowledge can have a practical output through further development. All four reciprocal systems have been intentionally designed to remain as flexible as possible, facilitating ongoing collaboration among architects, engineers, and manufacturers/builders. In the further design process, conducting simulations for specific solutions and making adjustments based on these analyses are crucial. Additionally, creating an optimised digital model could be a valuable step, integrating material parameters, structural performance, and overall design into a cohesive whole. In the further development of the systems, it is advisable to consider various mechanical fastenings and explore the use of different materials to optimise structural performance and minimise material waste.

5. Acknowledgements

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FORUM WOOD BUILDING BALTIC

HISTORIC WOODEN BUILDINGS

Technical state, renovation need, and performance of renovation solutions of Estonian wooden log houses
Alois-Andreas Põdra, Gert Air Allas, Aime Ruus, Elo Lutsepp, Targo Kalamees

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Technical state, renovation need, and performance of renovation solutions of Estonian wooden log houses

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Summary

The wooden log house is a predominant type of structure built before World War II in rural regions of Estonia. These buildings are subjected to deep renovation today. The purpose of the study is to determine the technical condition and renovation need, as well as performance of used renovation solutions of Estonian rural wooden log houses. The research uses the database of the consulting network managed by the Estonian Open Air Museum (208 houses, 4 years of data). The study identifies the most vulnerable structures of wooden houses, as well as likely causes of damages and evaluates renovation solutions recommended by consultants. The results of the study can be used to estimate national renovation volumes and develop renovation passport of wooden log houses.

Key words: Wooden log house; Renovation passport; Renovation strategy; Building vulnerability; Durability; Service life.

1. Introduction

The dominant architectural style of detached houses before World War II in Estonia was the wooden log house, which constituted the majority of structures in rural areas. These buildings represent an important part of Estonian heritage building stock. Because of their age and today's understanding of living style and quality, as well as environmental aspects, these buildings are usually subject to deep renovation today. Due to the size of the renovation volume, fragmentation, and the lack of capacity of the client, these buildings are often renovated by the residents themselves. Deep energy renovation may result in relatively large investments that may not be cost optimal if goals for energy savings are not linked to normal renovation measures, such as eliminating physical degradation, bad thermal indoor comfort or improving overall architecture. Buildings and its components are designed to have a long service life, traditionally 50 years. In practice we can see considerably shorter or longer. Over time the technical condition of building structures and systems continuously deteriorates and renovation needs become more evident. Changes in climate in the Baltic region has potentially increased the rate of decay for wood materials as conditions have become more advantegous for biological growth. In Estonia, the most notable increase in renovation activity is required among detached houses in order to achieve a decarbonized building stock. To successfully achieve the goals of this renovation wave and effectively address the personal needs of the homeowners, it is crucial to estimate necessary renovation volumes and develop universal renovation solutions that can be offered through a digital renovation passport. Consequently, the purpose of this study is to identify common damages, renovation need, and evaluate current renovation practices, which will serve as a crucial resource for the development of a digital renovation passport. The results are also applied for scaling renovation need and volume for the detached wooden housing stock.

2. Methods

We analysed the database of building survey and consultation reports collected between 2019 and 2023 by a national network of consultants, initiated by the Estonian Open Air

Museum. The database of reports included more than 300 buildings, summed up to more than 1000 investigated structures and building components. The purpose of building survey and consultation was to determine renovation need of houses and to give recommendations to homeowners for further repair and renovation of the house, which was summarized into an online report by the consultant. As the database included data concerning various building and construction types, our study focuses on residential wooden log houses, comprising 208 houses within the database of consultation reports. This data was analysed based on keywords concerning building type, building structure, construction material, construction elements, damages, recommendations, etc. This analysis provided statistical overview of pre-renovation technical condition and renovation need among the studied buildings, as well as evaluation of renovation recommendations communicated by consultants to home-owners. This data can then be used to highlight the most vulnerable structures and nature of likely damages, as well as causes, for developing typology-based renovation strategies and solutions. To scale renovation need and volume for the whole wooden houses stock, we used the dimensions and properties of two typical houses (a barn-dwelling and a detached house) built before World-War II in Estonia and building register data.

3. Results and Conclusions

The results provide insight into renovation needs from various perspectives, including load-bearing capacity, durability, hygrothermal performance, indoor climate (thermal comfort and indoor air quality), and energy performance. The building elements that are most in need of renovation are the external walls, roofs, and foundations, which require renovation in 77%, 63%, and 63% of the buildings, respectively. The primary cause of damage to the vulnerable structures is excessive moisture. Common sources of moisture include lack of ventilation, moist air, rainwater infiltration, and capillary moisture, introduced by weathering over time, improper construction techniques or lack of maintenance. Physical damages of wood elements are generally related to material decay or sagging. Additionally, decay in the foundation can be attributed to factors such as erosion of mortar, frost, insufficient plinth height, inadequate foundation depth, and inadequate moisture protection. Recommendations provided by consultants primarily focus on restoring and preserving the dwellings' original architectural appearance. As a result, they are deemed insufficient in terms of improving energy performance and indoor climate. This lack of comprehensive consultation is concerning as it fails to consider the potential for cost efficiency, minimizing disruption to occupants, and achieving a comprehensive end result. The absence of recommendations for enhancing indoor climate, energy efficiency, general living quality, and reducing the building's carbon footprint performance highlight the necessity for developing such renovation solutions and the importance of educating professionals and homeowners. Results are scaled to the Estonian building stock, showing the renovation need on national scale. For example, decayed lowest log courses will need 8500 solid cubic metres to 19 000 solid cubic metres of replacement logs to repair these damages on a national scale. The findings can be incorporated into the digital renovation passport, along with specific renovation goals related to a given house. This approach provides renovation solutions with proven performance and minimizes time wasted on discussing materials and renovation approaches with builders. Given the interconnectedness of structural elements and the potential for damage transfer, it is crucial that renovation works be planned holistically, considering the building as a whole over an extended period of time.

4. Acknowledgements

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Low carbon emission renovation of historic residential buildings

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Summary

A ~100-year-old wooden apartment building in Võru town centre heritage conservation area in Estonia was designed to nearly Zero Energy Building (nZEB). This study presents the results of life cycle assessment (LCA) calculations according to standards to analyse the carbon footprint value of different renovation strategies. Results of this study are indicating that it is possible to deeply renovate and achieve great energy performance value in buildings which are in the heritage conservation area while upgrading urban space and preserving the original building outcome. It is environmentally feasible to deeply renovate historically valuable buildings, insulating thermal envelope and restoring historical appearance.

Key words: Carbon footprint; Life-cycle assessment; Energy performance of buildings; Heritage buildings.

Introduction

Increasing need for building renovation, increases attention to building in heritage conservation areas, which have been currently left out of building carbon footprint calculation focus. The topic under investigation analyses and explores the possibilities for low carbon footprint solutions for environmentally valuable building renovation works. Study also analyses how renovation can restore buildings historical appearance. Which might have gone lost due to maintenance works over years. Research question is how additional thermal insulation influences carbon footprint of historic building while preserving original building proportions.

1. Method

1.1. Case-study building

The building used for reference is a two-story wooden log building (12 apartments, 617 m²), located in the historical heritage conservation area of the city of Võru in Estonia and it was built in the first half or middle of the 19th century (Figure 1 left). The reference case is a building with its original structure, stove heating, and natural passive stack ventilation. The building technical condition, moisture damages, indoor hygrothermal loads before renovation and need for renovation were determined by onsite survey.

The condition of the building's exterior facade and roofing was in such a state that it needs to be replaced both to protect the underlying structures and to improve the exterior of the building. This is a typical situation when the service life of the unmaintained wooden boarding is more than 40 – 50 years. Therefore, a comprehensive complete renovation has to be done anyway to extend the service life of the building.

1.2. Designed renovation solution and LCA assessment

Renovation solution utilizes the knowledge that though adding insulation to the external wall is most carbon-intensive, it is most effective in lowering heat losses and increasing the air tightness of the historic wooden building. If additional insulation is needed in any case, it is reasonable to choose the thickness of the insulation in such a way that heat loss can be minimized.

After renovation, the thermal envelope will be upgraded to achieve the Energy Performance Value (EPV) 90 kWh/(m²y). During the reconstruction work the original building proportions will be preserved and lifted outward to insulate the building (Figure 1 right). This requirements from the National Heritage Board will be fulfilled. After renovation modern heating and ventilation system and roof integrated solar panel system to produce on-site renewable energy will be added.

Figure 1. Kreutzwaldi 2, Võru building before renovation (left) and after renovation (right: Architects Karmo Tõra, Kaupo Kangro).

Life-cycle Assessment (LCA) calculations were used to provide objective information on the environmental impact during the building's 50-year service life. The proposed calculation for the LCA method is based on ISO 14040, European standards EN 15804+A2:2019 and EN15978, and the European Level(s) framework, which provide system boundaries. The Estonian methodology for carbon footprint of construction works summarizes the results from materials from grade to construction (A1–A5), replacement (B4), operational energy (B6), and end-of-life (C1–C4).

Results and Conclusions

The results proved that it is possible to deeply renovate residential building, which is located in the heritage conservation area to nZEB with preserving original proportions and appearance. New finding which appeared during this work that it is environmentally feasible to add proper insulation thickness, at least 200 mm. This is due to the fact, that in Estonian context operational energy (module B6) is dominating in LCA results and therefore, to achieve low carbon footprint value, a good thermal envelope should be added to the building.

This research highlights the critical roles of suitable energy sources and renovation strategies and provides essential guidance for environmentally sensitive urban development within historical context. Energy source is important component, as it forms in current context approximately around 90% from total building carbon footprint (B6 module). The comprehensive renovation of heritage protected buildings is beneficial in several aspects. This will reduce building carbon emissions, as the need for energy decreases rapidly after deep renovation.

Renovation will improve urban space as the outdated buildings will be restored and their historical appearance is restored. Important finding from the study was that is it not reasonable to add only 5-7 cm insulation to the walls or replace only external cladding, thus it will result increased carbon footprint value, however operational energy savings are not sufficient. The evaluation of technical requirements by the Estonian Heritage Board emphasises the need for more flexible and environmentally considerate approaches for renovation.

Acknowledgements

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Assessment of the Potential of Reconstruction of Historic Buildings

Elina Liiva[1], Helena Rummo[1], Kateriin Ambrozevits[2], Andres Ojari[1], Targo Kalamees[3], Siim Lomp[3]

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Summary

Purpose of the study is to make proposals to improve the reconstruction planning processes and update the requirements of it in the milieu-valuable areas. The method is to evaluate through questionnaires the need, potential and solutions for reconstruction of historic apartment buildings in the milieu-valuable areas.

The study concludes that justification of the current reconstruction requirements in the context of preserving certain milieu-values may remain incomprehensible and this makes the homeowners reluctant and neglectful to these requirements. As a result the culture of step-by-step renovation appears, which makes the general view of the historically valuable area eclectic and promotes the use of inappropriate materials. The research concludes that a holistic approach to the building gives architecturally better and technically more sustainable results and the requirements must support that.

Keywords: Renovation; Reconstruction; Historic Buildings; Milieu-valuable Area; Heritage Protection.

1. Introduction

In connection with the long-term strategy for the reconstruction of the Estonian building stock in 2020, within the framework of the LIFE project „Pursuing Estonian National Climate Ambition through Smart and Resilient Renovation", the development of recommendations to increase the efficiency and quality of the buildings was started. The motivation of the study is the questionability of the justification of the reconstruction requirements for buildings located in milieu-valuable areas and the effectiveness of the implemented construction solutions, both in the context of preserving the various values of milieu-valuable areas and in the context of the effort to increase the energy efficiency of buildings. The aim is to provide recommendations for updating the requirements and improving the efficiency of the reconstruction planning process by evaluating the technical condition of the buildings and their suitability for the environment with the help of on-site observation. Through recommendations, the design process is made faster, building is made more cost-effective for the owner, and awareness of sustainable reconstruction is raised. For this purpose, various specialists involved in the reconstruction of historical buildings were also involved in this study.

2. Methods

The questionnaire is structured to evaluate three aspects: building material and finishing, geometry and technical situation. In the case of the building's material, finish and geometry, originality is assessed, and in the case of the technical situation, the need for renovation. The evaluators are specialists of various professions related to the reconstruction of the historical building - architects, engineers, heritage protection specialists. During the survey, the buildings have been evaluated in two ways - as a whole and by parts of the building. In the first case, it is evaluated how does the building as a whole fit into the surrounding milieu and a more general evaluation is made of what element most negatively affects the building. In the second case, the building is disassembled into parts, and each part of the building is evaluated through each aspect.

Such an approach provides an overview of how the modification of the original has affected the aesthetical and technical situation in the milieu area. It also gives an understanding how a single element could affect the impression of the whole.

3. Results and discussion

The suitability of the specific part of the buildings for the milieu was assessed in three stages: whether it ruins, affects or does not affect the milieu. The analysis revealed that the opinions of the three professions differ gradually in all three assessments. The most critical were representatives of heritage protection, then architects and then engineers.

With most of the observed buildings, all specialists agreed that even if some specific element does not meet the requirements of the milieu area, it does not necessarily affect the suitability of the whole building in the milieu-valuable area.The questionnaire about the whole of the building allows us to identify the element that affects most the overall impression of the building. This gives an indication of which of the existing requirements are most rarely followed during the reconstruction and which of the requirements needs to be explained the most in the future to the home owners.

Based on the analysis, the suitability of the buildings for the milieu-valuable area is better if all the structures of the building are reconstructed simultaneously and thoughtfully. For example, if the facade is brought outside with the insulation of the building, then other parts of the building - eaves, staircase, plinth and windows - should be brought outside also in order to maintain the proportions and eliminate thermal bridges. However, treating it as a whole does not always have to mean simultaneous reconstruction of the entire building but the reconstruction could be divided into stages during the planning phase. This excludes situations where during the reconstruction of the next building part, the previously completed work must be partially demolished or redone.

For the owners of buildings located in a milieu-valuable area, certain rules have been established for the reconstruction of buildings, which should ensure the preservation of the historical environment. The analysis shows that if the building is treated as a whole, it is possible to ensure the architectural appearance and engineering performance after reconstruction, even if other techniques and materials are used besides the traditional options. In historically valuable areas, there are buildings that have been preserved or reconstructed true to their era, but there are also those cases where various stages of construction have significantly distorted their original appearance. Could those be the buildings that we could implement modern architectural solutions while also striving towards higher energy efficiency and taking into account the historical context of the surrounding urban environment?

4. Conclusions

The analysis revealed that the phased renovation of buildings creates the best outcome. This is evident both in the non-functional engineering solutions of various structures and in the architecturally eclectic exterior (that does not improve or correspond with the historic area) of the buildings that have been reconstructed step-by-step without any foresight. On the other hand, a complete renovation can provide a suitable and constructionally functional result for an milieu-valuable area, even if some individual elements of the building cannot be considered to meet the valid reconstruction requirements.

5. Acknowledgements

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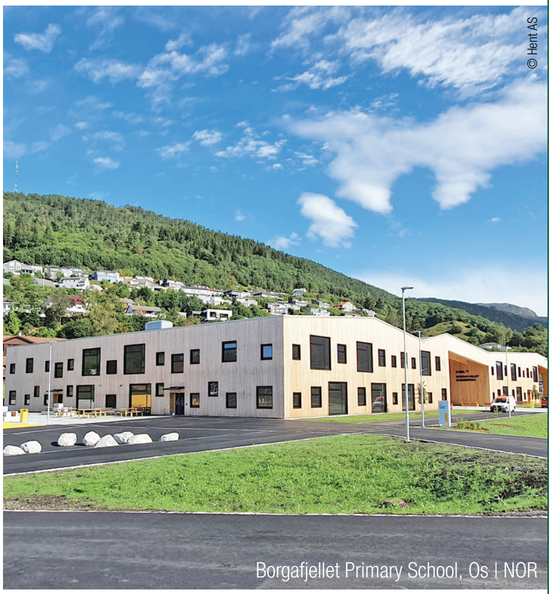

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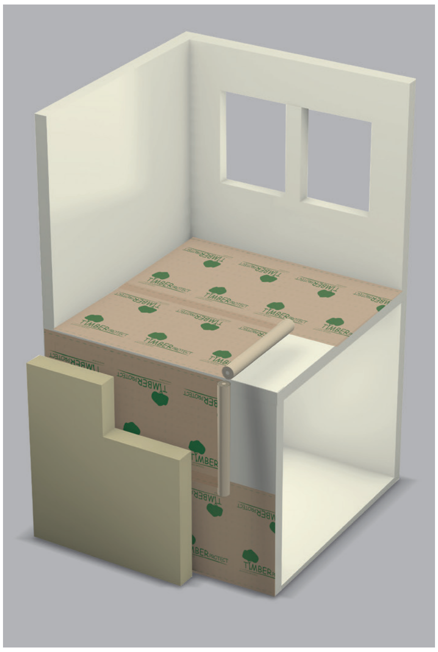

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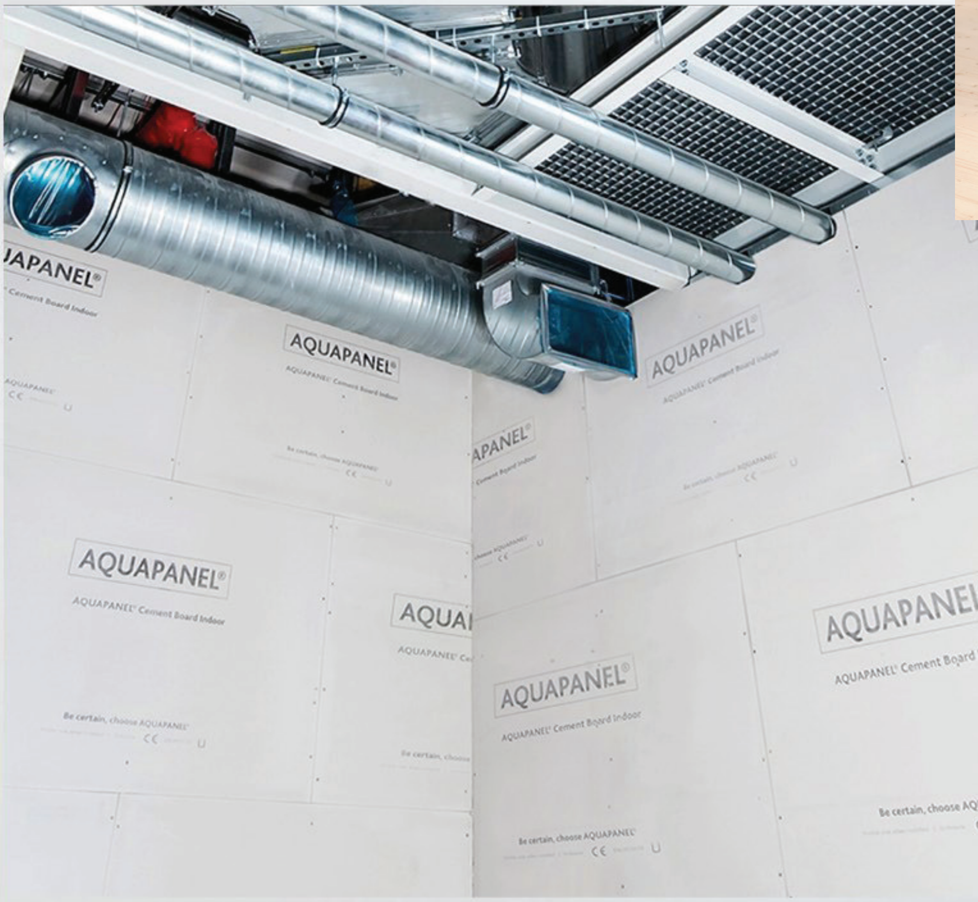

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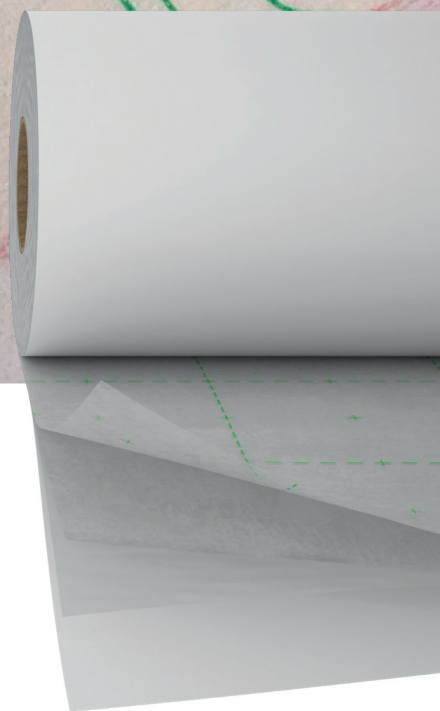

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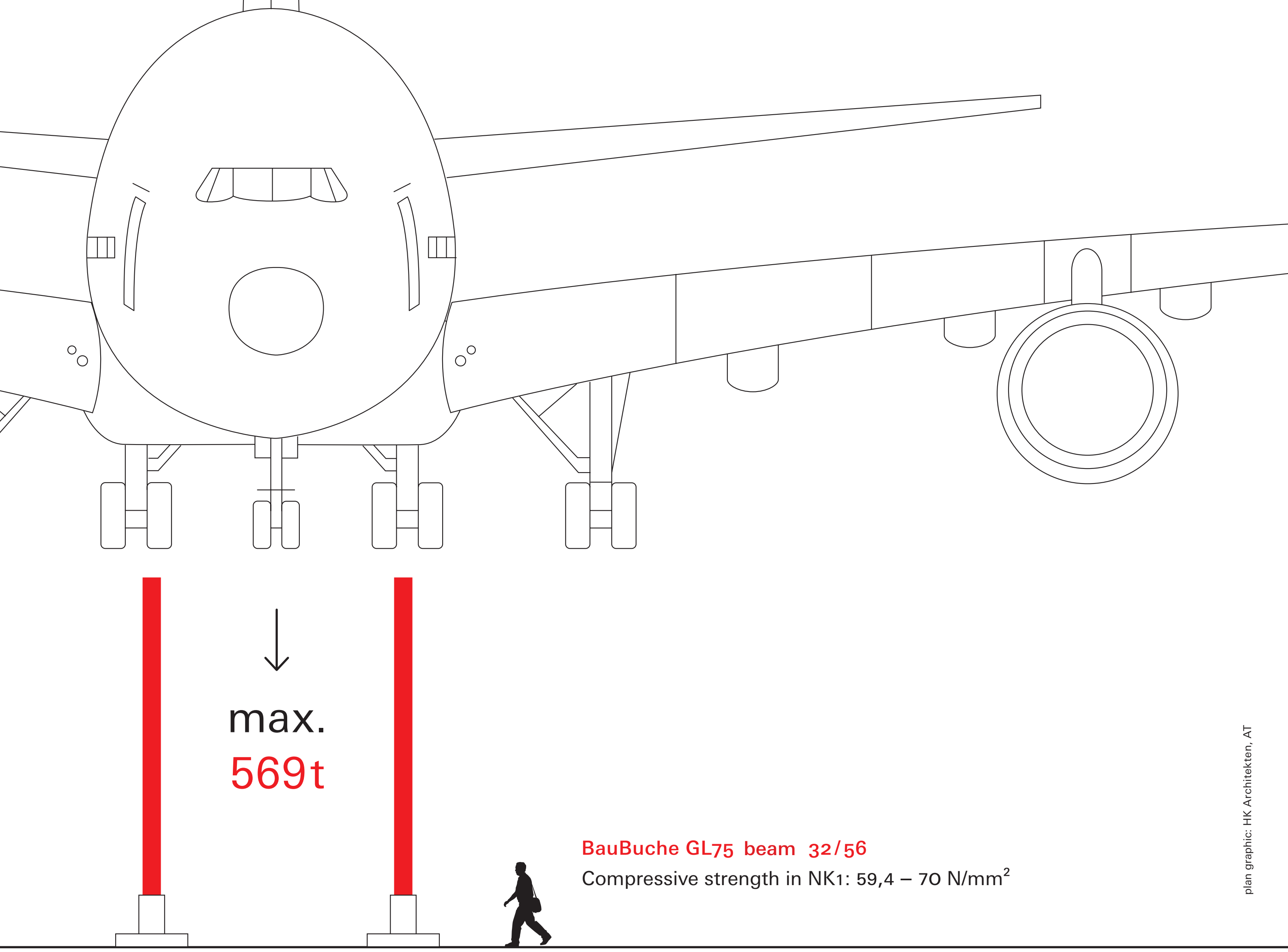

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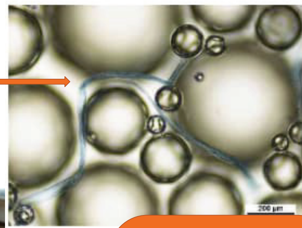

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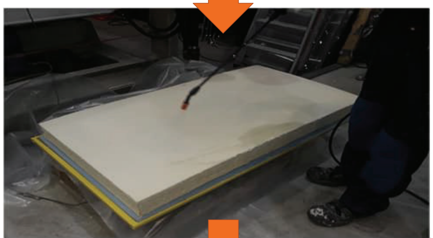

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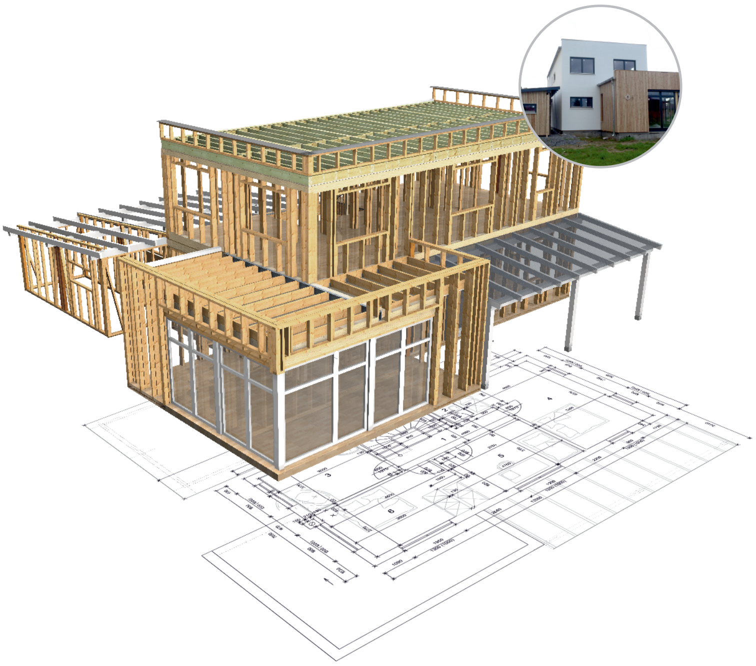

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