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Engineering design for an efficient assembly of multi-story cross-laminated timber structures

A survey conducted between November 2020 and November 2021

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ABSTRACT

Design for efficient assembly is essential to further enhance the competitiveness of cross-laminated timber building systems for multi-story timber structures. This requires a holistic view from the design of the load bearing structures by structural engineers, over the production, pre-fabrication, and transport to the assembly of the structural elements on-site, which often is done by different companies with input from different stakeholders in the construction process. Especially the design of connections between CLT elements, and CLT and other construction materials and products, as well as the size of CLT elements and possibilities for pre-fabrication are crucial for an efficient assembly process. The paper summarizes findings from expert interviews with a focus on Sweden along the before-mentioned value chain, with the aim to identify current practice and potentials for further improvements. Design for efficient assembly starts at the early-stage design and involves all stakeholders in the design construction process. The reduction of uncertainties in the design and assembly process of multi-storey CLT structures as well as knowledge and experience transfer could lead to more efficient design. The identified requirements for efficient assembly should be combined with a life cycle analysis to quantify the potential for a reduction of the carbon footprint of CLT-based building systems, which is the aim of the ongoing research project '*Improving the competitive advantage of CLT-based building systems through engineering design and reduced carbon footprint*'.

The authors would like to thank all interview partners for their participation and for sharing of their knowledge and experience. This research work is part of the research project '*Improving the competitive advantage of CLT-based building systems through engineering design and reduced carbon footprint*' funded by the Knowledge Foundation (project number 20190026).

KEYWORDS
survey, cross-laminated timber, multi-story structures, design, assembly, efficiency

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Table of Contents

Introduction

Cross-laminated timber (CLT) has become an attractive and competitive construction material for multi-story and even high-rise buildings. The crosswise layered structure of wooden boards makes it suitable for wall slabs and floor plates with large dimensions. Despite increasing use and production capacities [1], there is a need for deeper understanding of certain mechanical properties of CLT and its performance in structures. Since it still is a rather new wood-based construction system, there is a potential to further enhance the efficiency and competitiveness of CLT-based building systems. The efficiency can be increased by the engineering design and production of CLT elements based on the raw material, and the design of connection systems, but also by means of risk assessment and management during the service life, as well as by a design for re-use and circularity. The combination of these aspects in a synergistic approach can substantially reduce the carbon footprint of CLT-based buildings [2].

Construction speed and efficiency depend on the reliability and efficiency of connector systems. Connections are a crucial part of CLT structures necessary to guarantee structural safety, robustness, and load transfer over the service life of the structure. The design of connections is decisive for the global behaviour and load distribution in timber structures, not only under normal use conditions but also under exceptional loading cases. The performance of structures under fire or the acoustic behaviour of elements and structures are significantly affected by the detailing of the connections. Thousands of screws or nails need typically to be installed in CLT buildings. In addition to the structural safety, the type, size, and number of connectors used affect labor and installation time and therefore direct cost and carbon cost of construction.

A design for efficient assembly is essential to further enhance the competitiveness of building systems of cross-laminated timber for multi-story timber structures. This requires a holistic view from the design of the load-bearing structures by structural engineers, over the production, pre-fabrication, and transport to the assembly of the structural elements or prefabricated units on-site, which often is done by different companies. Especially the design of connections between CLT elements and CLT and other construction materials and products, as well as the size of CLT elements and possibilities for pre-fabrication are crucial for an efficient assembly process.

There are no standardized connection systems for CLT structures but a broad variety of supplier-specific fasteners and connectors. Complementary to timber connection design models and properties given in design standards (see, e.g., [3]), some basic CLT-specific design properties are provided in CLT handbooks (see, e.g., [4]). There are however no selection criteria for certain types of fasteners and connectors, and this may constitute a hinder for inexperienced engineers who want to start working with CLT. Moreover, a lack of design provision and guidance may lead to challenges and inefficiencies in the design and may furthermore, lead to inefficiencies in the production and assembly process. On the other hand, specialized engineers, production, and construction companies have built up valuable knowledge and experience related to design for efficient construction, which, if collected and disseminated, profit gain the wood-building sector in general.

Design for disassembly, re-use and circularity was not included in the interview study but is another important question as related to efficiency of connection systems.

The paper summarizes findings from expert interviews in Sweden and Austria along the before-mentioned value chain, with the aim to study current practice, collect and document examples, and identify potentials for further improvements of connection systems. The work was based on interviews with open-ended questions and complemented by the perspective and experience of the authors, which represent researchers in the field of timber engineering and practicing engineers working with cross-laminated timber-based building systems along the value chain. The study aimed at identifying the needs for further research and development of CLT-based building systems. It is part of an ongoing research project that is performed in collaboration between academia and industry partners. The project aims at improved competitiveness of CLT-based building systems through more efficient utilization of raw material and improved connection and construction techniques, improved confidence (mitigating uncertainties and risks) through long-term building risk assessment and management, and the quantification of the potential through LCA models of CLT buildings [5].

Interview Study

The survey based on expert interviews was done with a selected number of construction and consultant companies in Sweden, with different experience in the design and assembly of CLT structures. In addition, two experienced engineers from Austria, as related to structural design and production of CLT structures, were interviewed as well. A qualitative research methodology was used based on open-ended questions related to the holistic construction process from the design – to production and pre-fabrication – transport – and assembly on-site. For the purpose of the study, the method was chosen to secure vivid and accurate accounts based on the interviewee's personal experience in multi-story CLT buildings design and assembly.

Interviews were performed within an ongoing research project [5] and by a sub-project group consisting of academic and industry partners. The expert area of the academic project members was in the field of timber engineering, while the industry partners included producers of CLT, producers of mechanical fasteners and connection systems and a construction company.

The interviews were done from November 2020 to November 2021, through online meetings, personal meetings, and study visits with a discussion at the construction site during assembly. The questionnaire contained questions related to

- the process and criteria for the selection of connection systems and connectors for CLT,
- the process and criteria for the combination of connection systems with CLT and other construction materials and products,
- provisions for an efficient assembly process, including design, production, and construction, of CLT structures with a special focus on connections and CLT elements, and
- challenges in the design for efficient assembly and in general challenges in the design of CLT connections, including the potential for a design for more efficiency.

The selection of the interviews was done based on the network of the project group and might not be representative for the construction industry in Sweden in general. In total, representatives of eight companies were interviewed. This included three consultant companies working with the design, two construction companies working with the assembly and construction, and three companies working with the design and the assembly and construction of multi-story CLT buildings. It should be noted that none of the interview partners represented the production of engineered wood-based products.

Results

The designer's perspective

Engineers designing multi-story CLT structures are, in addition to a non-standardized CLT product, facing the challenge of a large variety of suppliers and products of mechanical fasteners. There is a broad variety of product properties regulated in ETAs, which is especially difficult for engineers inexperienced in the design of timber structures. For more experienced engineers, the choice of connection system is mainly based on previous experience. The selection of a specific product is however often done at a later stage of the process and by the construction company, while requirements need to be chosen in the design and specified in the procurement. The latter process makes the decision for more advanced CLT-specific connection systems difficult since they do not allow for a broad competition, which is especially required in public procurements. Connections with angle brackets and screws or nails are therefore often favoured. More advanced connection systems however could lead to more efficient structural systems and a more efficient assembly process.

Mechanical fasteners for timber structures are often exclusively tested for structural timber, while design rules for the use in CLT are missing. This requires assumptions in the engineering design based on handbooks for CLT or national appendices to the Eurocode 5 [3]. This is related to the embedment behaviour and withdrawal behaviour of the mechanical fasteners in the layered wood-based elements, but also to the design models for the calculation of lateral and axial strength and stiffness of connectors, and possible group effects in multiple fastener joints.

Not only stiffness and strength of the connection but also acoustics is an important design criterion, which relies on a suitable detailing of the connections. For efficient design and competitive structural systems, not only safety, serviceability, and durability, but also production and easy assembly of connections on-site needs to be considered.

A problem structural engineers are facing is a lack of standardized structural connection details. CLT-based building systems are still rather young and there is an ongoing development process where experience from earlier projects is used to enhance the efficiency. This is especially a hinder for engineers who do not have long experience in the design of timber structures and can lead to higher costs. There is a high number of different construction details in CLT structures and individual, project-specific solutions are work intensive.

Standardization of construction details is complicated by the lack of standardization of CLT elements and connection systems and fasteners. Design engineers experience less difficulty with CLT products, while changing the connection systems is more laborious.

The design of CLT structures is more and more done based on 3D structural analysis models. 3D models are mainly used for global structural analysis, where connections are not explicitly considered. The design of connections is subsequently done in separate design tools. The interviewed engineers consider the design for the joint's resistance, and not the design for the resistance of individual fasteners, as most efficient. Corresponding strength values for various loading directions in relation to the CLT material directions, are often provided in fastener manufacturer's handbooks. It would be even more efficient if the design of both, the CLT elements and the connections, could be done in one computer model. This is however nothing the interviewed engineers are currently working with. Such an integrated model would also simplify an iterative design procedure where the selected connection properties are fed back into the global structural analysis.

The computational design requires interfaces and interaction with, on the one side, architects and, on the other side, the production. The latter is essential for time planning since the design needs to be finished before the production can start. Moreover, the developers/customers play an important role in the design process. The engineers often experience a lack of knowledge or awareness of the developers, and the architects as regards the design of CLT structures and connections. Hybrid or timber composite structures are hardly requested by the developers and architects, but either concrete or timber structures. This constitutes a barrier for more efficient structural solutions.

The architectural design strongly affects the efficiency and thus the costs of the structure. Time for optimization in the structural design is often missing but could be made possible in a more integrative design process by involving structural engineers already in the early-stage design.

Missing experience of the structural engineer and uncertainties in the design process may lead to over-dimensioned structures and a high number of mechanical fasteners. There are several risks that need to be handled. The type of building and possible consequences of a failure governs the corresponding safety class or consequence class according to design standards. The designer even needs to consider the experience of the assembly team in order to ensure an execution quality within the considered uncertainties in the design. If several actors in the design process, such as the suppliers, the producers, the designers, and the constructor, add safety margins, at the end, structures will be very much over-designed.

The production and construction company´s perspective

For an efficient construction based on the design by the structural engineers, an understanding of the capacities and possibilities of the production and construction chain is already required in the design. This is naturally more difficult in early-stage design, where products and producers/contractors are usually not decided for.

The possibilities of pre-fabrication should be exploited and precise instructions, as e.g., creating an understanding of the importance of positioning of connectors, to the assembly team is required to be efficient on-site. A simple prefabrication measure for efficient assembly is pre-drilling of screw holes or marks for the position of the screws, placed already in the factory. This allows for a fast insertion and correct positioning on the construction site.

The interviews showed that inclined self-tapping screws in combination with butt-joints of CLT elements are preferred by the assembly teams, as compared to angle brackets with mechanical fasteners. Inclined screws are easier to handle from the production and assembly perspective and simple butt joints give a better weather and moisture protection of the CLT during the construction.

The design engineers need to decide on the number and dimension of mechanical fasteners and therefore, the experience of the construction and assembly teams is important. Smaller diameter fasteners can be inserted faster with less force, but then a higher number of fasteners is required. However, fewer and larger diameter screws as compared to many small diameter screws were preferred by the interviewed construction companies. Their experience was a faster assembly with larger diameter screws. A fast assembly is important to avoid moisture-related risks, especially when building without weather protection.

Inclined screws have another advantage as compared to angle-brackets, as they do not protrude from the CLT surfaces. This is not only preferred for visible/exposed CLT elements in structures, but also for work safety and for easier installation work on CLT floors. Air tightness of the structure, moisture protection during construction and acoustics are important in the assembly of CLT structures.

The size of CLT elements themselves constitutes another potential for increasing efficiency. The use of large CLT elements avoids the need for many connections. The size of CLT elements is however limited by production facilities, transport, and easy handling on-site. Increasing the length of CLT elements is therefore often combined with smaller widths, to limit the lifting requirements on the construction site. Processing of CLT elements in the factory for increased prefabrication is possible but may lead to higher costs especially when the elements must be processed from both surfaces.

In the interviews with the construction companies, especially the connection between concrete lower floors or the concrete foundation and the CLT walls was emphasized as an important construction detail. One reason for that is that tolerances are different for timber and concrete. This needs to be considered in the design of the connections in order to allow for an efficient assembly. Different solutions of this construction detail from case studies were found. The problem of different tolerances between concrete and timber is increased due to creep deformations that are different in the two materials as well. Most of the creep deformation however develops during the construction phase.

Conclusions

Conclusions from the interview study were drawn as a holistic view from and with the expertise of the project group. The following requirements were identified for an efficient design of connections and efficient assembly of multi-storey CLT structures:

- Uncertainty in the design and assembly process of multi-story CLT structures can lead to strongly over-designed structures.

- There is a need for knowledge transfer and dissemination of experience gained from executed construction projects to facilitate efficient design. Structural engineers do not only need product properties but also examples of construction details with design calculation examples. This is especially important for engineers unexperienced in the design of CLT structures.

- Standardization of CLT products, connection systems (rather than mechanical fasteners) and construction details can lead to more efficient design and needs to consider production and assembly facilities.

- Prefabrication, e.g., through pre-drilling of screw holes can shorten assembly time and reduce construction risks.

- Design for efficient assembly starts at the early-stage design and involves all stakeholders in the design construction process.

Design for disassembly, re-use and circularity was not included in the interview study but is another important question as related to efficiency of connection systems.

Finally, the above identified requirements for efficient assembly should be combined with a life cycle analysis to quantify the potential for a reduction of the carbon footprint of CLT-based building systems, which is the aim of the ongoing research project [5].

The authors would like to thank all interview partners for their participation and for sharing of their knowledge and experience. This research work is part of the research project '*Improving the competitive advantage of CLT-based building systems through engineering design and reduced carbon footprint*' funded by the Knowledge Foundation (project number 20190026).

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