WCTE 2014 Quebec City Canada August 10-14
World Conference on Timber Engineering

MULTI-STOREY RESIDENTIAL BUILDINGS IN CLT – INTERDISCIPLINARY PRINCIPLES OF DESIGN AND CONSTRUCTION

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ABSTRACT: Cross-laminated timber (CLT) is a very efficient and powerful building material and thus recently discovered for the erection of multi-storey timber towers. In our paper, we focus on building science and services related topics regarding these constructions. Thereby, we firstly identify moisture ingress as main problem worsening their durability and thus discuss possible detail solutions for both external and internal critical building zones such as flat roof, balcony system and wet rooms. The second main topic we are concentrating in this paper are simple measures to increase the efficiency of CLT constructions by simplifying and improving their structural systems (floors, walls and connections). Both topics are connected by the major importance of interdisciplinary thinking and acting when building with CLT.

KEYWORDS: Cross-laminated timber; moisture ingress; building science and services; efficient detail solutions

1 INTRODUCTION

During the last twenty years, cross-laminated timber (CLT) has raised up to one of the most commonly used building materials in modern timber engineering. A high-sophisticated and automatized manufacturing process, the standard nowadays, allows a precise production of large-sized CLT elements mainly used as structural components in building industry. The fact, that CLT has become an industrial product and its wide area of application, which especially includes housing, timber bridges as well as factory halls, currently lead to worldwide sales figures of about 500,000 m³ [1]. Consequently, an increasing number of research activities in the scientific field of timber engineering deal with investigations concerning the structural behaviour of CLT and thus form the knowledge basis for multi-storey residential building projects in solid timber construction (STC), e. g. in Bergen (NO), Melbourne (AU), Milano (IT), London (UK) or Vienna (AT) with up to 14 storeys [2], see Figure 1.

The motto “everything is possible” going along with this recent development even leads to studies focusing on the realisation of multi-storey timber towers reaching building heights of almost 100 m (or 30 storeys) in the next few years [4]. Benefits provoked by this process such as the establishment of new key markets in inner city areas and the possibility to create natural, lightweight and CO_2 neutral alternatives if compared to similar constructions in reinforced concrete are worth to be mentioned.

Figure 1: *left: project “Stadthaus, Murray Grove”, London, UK; right: project “C2 East”, Melbourne, AU [3]*

When thinking of comparative and superlative, motivated by the principle feasibility in static-constructive terms (ULS, SLS, fire and earthquake design, connection techniques, etc.), we should not forget basic requirements regarding the construction of such high-rise timber towers,

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which have to be considered as well. Due to its huge potential in terms of two-dimensional load-bearing in-plane and out-of-plane as well as its high grade of prefabrication, CLT is nowadays seen and also applied "as the new concrete". In fact, wood is a natural product and, consequently, does not share the same physical properties with concrete. To avoid expensive rehabilitation works caused by hidden and uncontrollable moisture ingress (see e. g. Figure 2), external and internal constructive wood protection has to be seen as one of the major tasks when planning a multi-storey timber building in CLT. Critical building parts such as flat roofs, balcony constructions or wet rooms, which are situated in contact with external surface water or internal water lines, should be designed and realised by thinking and acting interdisciplinary to guarantee the durability of the building as basic requirement given in EN 1990 [5].

Figure 2: *Damage of the CLT bearing structure caused by moisture ingress in a wet room*

Consequently, in the following sections we especially concentrate on these interdisciplinary issues, subdivided in external and internal critical building zones, and discuss their possible solutions. The previous mentioned increasing worldwide sales figures of CLT elements (and also of wood based products in general) in combination with a rapidly increasing energetic utilisation of wood (especially in Central Europe), will lead to conflict situations regarding the distribution of resources in the next few years. Efficient structural systems as result of an intelligent interdisciplinary planning process are seen as contribution to a more resource-friendly and economical way of using CLT and thus also discussed in this paper.

2 EXTERNAL CRITICAL ZONES

A typical façade cross section of a multi-storey timber building in CLT is shown in Figure 3. Hereby, critical buildings zones, such as the flat roof detail, the façade insulation system (including its wall-floor-wall joints) and the balcony construction are outlined and discussed in the subsections 2.1 to 2.3. The design of the socket detail (joint of the basement and the first storey walls) is seen as critical building part for timber constructions in general and thus not focused in the frame of this paper. Nevertheless, it is worth mentioning, that a mineral plinth with at least h = 300 mm over the outer base level should be situated in order to avoid damage of the timber construction as consequence of water ingress at ground level (see also [6]).

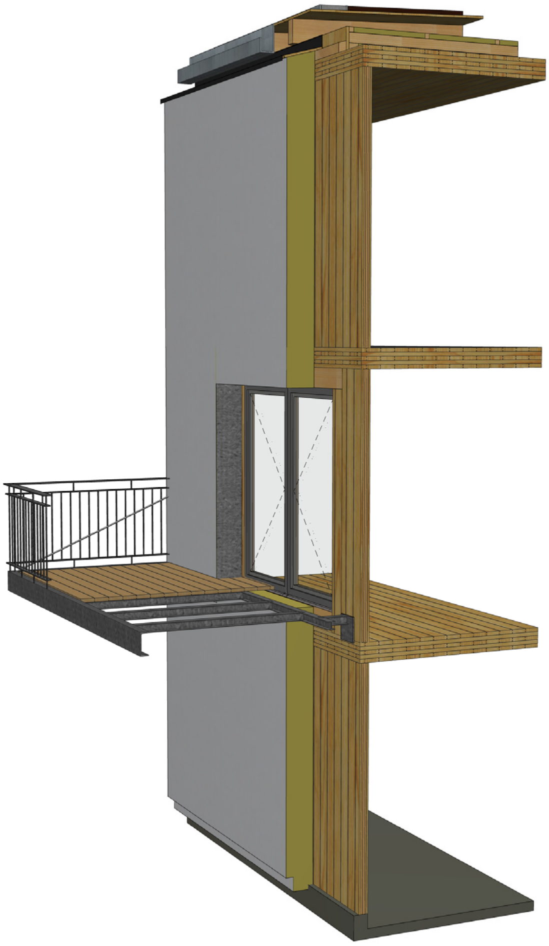


Figure 3: *Schematic illustration of an STC façade cross section*

2.1 FLAT ROOF

Deviating from the detail shown in Figure 4, common roofing systems of STC buildings are often equal to those standardised for multi-storey buildings in reinforced concrete (RFC) or steel. Normally, they consist of a suspended ceiling (gypsum boards), a bearing layer (RFC, steel or CLT), a vapour barrier (also used as provisional roof sealing), a synthetic insulation layer (EPS) and a final roof sealing. With regard to this assembly, there is a certain risk of hidden moisture ingress in case of a leak in the protective coat, especially for large roof areas with low inclination for water drainage.

Consequently, Figure 4 and Table 1 show a possible solution for a durable timber roof system with a special regard to moisture protection. The main difference to the assembly mentioned before is the back ventilation of the flat roof construction. Due to the permanent air change in this zone, it not only provides a certain degree of protection against overheating in summertime but also serves as second protective coat in case of unexpected moisture ingress of the wooden under roof where construction can dry out. Therefore, it makes sense to construct the back-ventilation zone inclined. As given in Table 1, its quite big thickness of at least 600 mm makes it also accessible for maintenance.

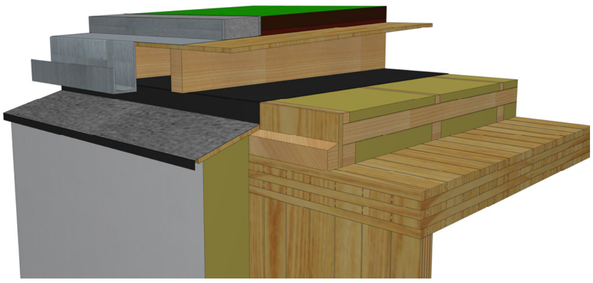


Figure 4: *Proposal for a flat roof construction in CLT [7]*

Table 1: *Assembly of the flat roof construction shown in Figure 4*

Layer (from top to bottom)	Thickness (mm)
Mineral plant substrate (layer of vegetation)	90
Protective coat with filtering features	30
Roof sheeting (PVC free)	10
Fleece	-
OSB panel	20
Timber rod / ventilation zone	> 600
Roof sheeting (water vapour permeable)	20
Thermal insulation with timber slats in between (3 layers)	250
Vapour retarder	-
CLT element (5 layers)	180

2.2 FAÇADE INSULATION SYSTEM

Similar to the situation for flat roofs illustrated in section 2.1, many planners recently apply façade insulation systems such as ETICS (**e**xternal **t**hermal **i**nsulation **c**omposite **s**ystem), traditionally used for multi-storey RFC and brick buildings, to solid timber constructions with CLT (see Figure 5). The main reason therefore is their economic advantage if compared to a traditional back-ventilated wooden construction. Because of no European standardisation related, these system solutions, consisting of the components "surface coating", "reinforcement", "insulating material" and "fastening", are regulated by European Technical Approvals (ETAs).

It is worth mentioning, that these approvals also declare suitable base coats (if mineral then brick or concrete wall; if organic then wood-based panel material), which are allowed for application of the concerning ETICS. When studying these documents it can be seen that the majority of these systems (especially those with synthetic insulating materials such as EPS) are decidedly not approved for structures consisting of plate-shaped wooden composites.

Approvals of further insulating materials, such as mineral or organic wools, limit the allowable type of base coat to certain specified products, so that CLT elements are only allowed in a few cases. Nevertheless, external wall assemblies in CLT with mineral wool panels as insulating material are commonly used nowadays and proven to be suitable.

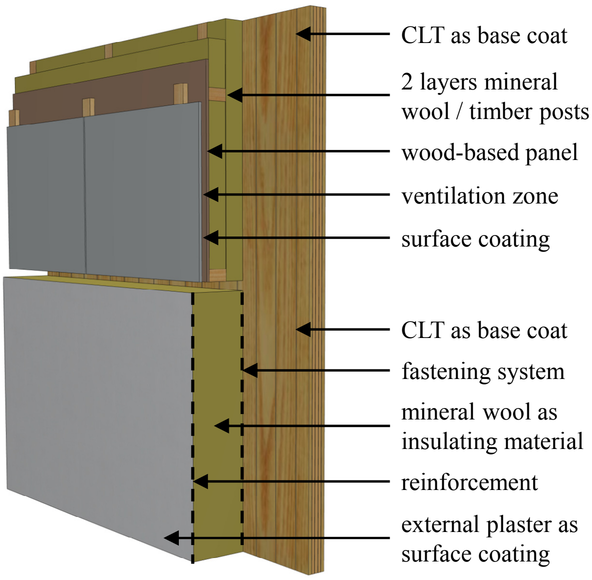


Figure 5: *Schematic illustration of two wall assemblies; above: preferred back-ventilated lay-up; below: ETICS with CLT as base coat*

In addition to this grey area in law, higher vertical deflections of a timber building – if compared to an RFC construction – are worth to be noted in this context. The wall-floor-wall joints in the first storeys, where the CLT floor element is stressed by compression perpendicular to the grain direction of its boards, is seen as possible damage zone of the glued and thus quasi-rigidly connected insulating material and surface coating. To avoid crack formation in this area, which may cause a loss of insulting performance as well as uncontrolled moisture ingress, two possible measures can be proposed: (a) application of mechanical connections for the insulating boards (out of a more flexible material, e. g. wood-based fibreboards), which also improves the vapour diffusion behaviour, and/or (b) the arrangement of vertical expansion joints in these areas.

2.3 BALCONY CONSTRUCTION

In contrast to the thermal separation in RFC constructions, CLT cantilever floor systems serving to support balconies are often applied in multi-storey timber buildings. The general feasibility due to a better thermal behaviour (again if compared to RFC), an easy and economical way of assembling as well as possible benefits in static constructive terms (the cantilever's gravity load decreases the field moment) are the main reasons of their popularity.

With regard to these advantages it should not be forgotten, that cantilever and inner field as parts of this structural floor system (a) have to be designed for different service classes (SC) according to EN 1995-1-1 [8] (SC 1 conditions are hardly to be provided, even if the whole balcony part of the CLT element is thermally insulated) and (b) have different lifetimes requiring the principle possibility of replacement. In addition, the existence of gaps in the CLT elements may enable uncontrolled air and moisture transfer into the bearing structure.

As shown in Figure 6, one possible solution of this detail situation may be a balcony system as steel secondary construction. Compared to the previously discussed cantilever system, the economical effort (the steel structure is more expensive but needs no moisture and thermal protection) as well as the speed of assembling as consequence of a high grade of prefabrication are roughly equal. In addition, the following advantages are worth to be mentioned: (a) There's no necessity of any height compensation due to the additional floor lay-up and (b) the construction is easily to replace in case of damage or when its lifetime is over. Optical disadvantages or restrictions of the architectural design due to additional supporting can be solved by hidden anchoring in the level of the handrail. The arrangement of punctually situated and bending resistant joints in the level of the CLT floor element (e. g. in form of a new system connector) is another solution of this topic.

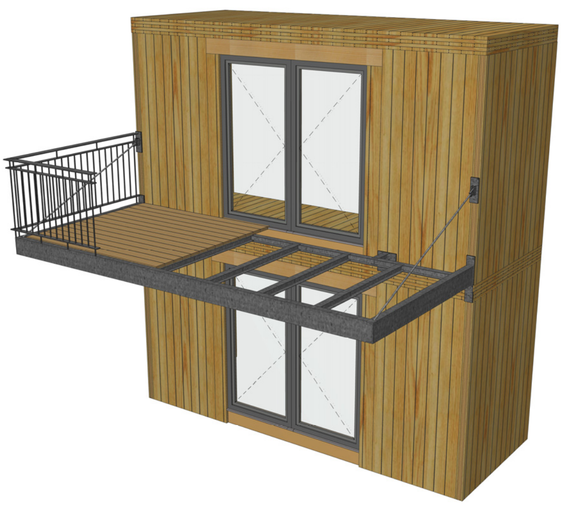


Figure 6: *Balcony system as steel secondary structure [7]*

3 INTERNAL CRITICAL ZONES

In addition to the aim of guaranteeing a reliable and durable building envelope for multi-storey residential buildings in solid timber construction with CLT, also vulnerable internal zones are worth to be focused in detail.

As shown in Figure 2, hidden and uncontrolled moisture ingress in the bearing structure as consequence of either a leak in the water service pipe system or in the protective coat of a wet room reveal the weaknesses of a timber construction dramatically. One main reason for such damage cases is again the wrong philosophy using CLT elements in an equal way as RFC is used in a building. Thus, building services solutions, suitable for solid constructions with mineral materials where moisture ingress rarely harm the structural performance are often copied:

- Arrangement of rising pipes either directly in the CLT element (in prefabricated slots) or in the facing formwork with no protective coat to the timber wall.
- Arrangement of distribution pipelines in the additional floor assembly; often in the filling material between the resilient layer and the CLT element. Of course, a PAE film separates both pipelines and timber floor element, but the risk of at least one damage case during building lifetime is quite high.

With regard to this situation, especially when thinking about timber towers with up to 30 storeys, the question, how a rotten CLT floor or wall element is going to be replaced in an altitude of e. g. 70 m, still remains. Needless to mention, that an interdisciplinary design process – starting with the early stage of the project – may prevent such situations. One possible water line run solution of a solid timber construction is shown in Figure 7 (the room arrangement as well as the building materials used are from an architectural study, see [9]). There, the rising as well as the distribution pipes are structurally disintegrated:

- The water supply and delivery system is mainly situated in the transition zone between the flats in STC and a central staircase in RFC. All wet rooms directly adjoin this inner core.
- All additional rooms with a need of water supply (kitchens, etc.) or radiators of the central heating are reached by a pipe system arranged in the suspended ceiling.

It has to be noted that both suspended ceiling and the shell (covering the transition zone) can be easily replaced without any damage of the bearing system in case of moisture ingress. Moreover, a simple possibility observing the pipe system (inspection doors and observation channel; including sensor technique in high sophisticated case) is given.

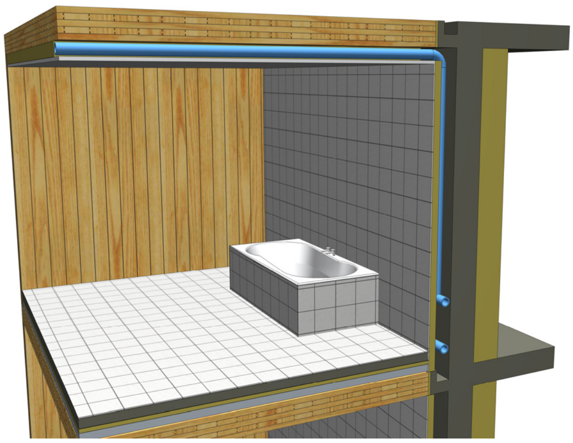


Figure 7: *Timber-adequate line runs in a CLT structure [7]*

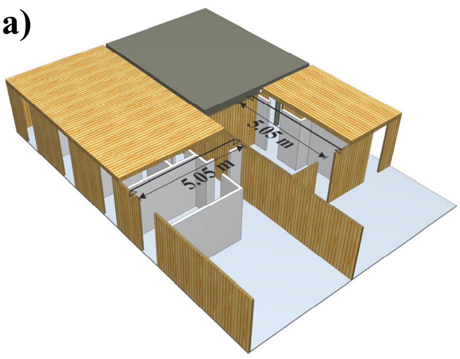
Of course, multi-storey timber buildings won't always be erected including an inner RFC staircase in future. Thus, there's a serious need of building services related detail solutions, especially regarding the way, the water supply and delivery system is situated in the construction. Some first proposals are given in e. g. [10].

4 EFFICIENT STRUCTURAL SYSTEMS

4.1 FLOORS

Due to its typical lay-up (uneven number of boards/layers with crosswise orientation), CLT has a significantly lower shear stiffness if compared to a unidirectional oriented timber product. Consequently, CLT elements (a) have to be designed with a method considering this phenomenon (e. g. as transversal-flexible-in-shear beam according to Timoshenko, see [11,12]) and (b) are predominately decisive regarding serviceability limit state (SLS, deflections and vibrations). Thus, common l/h-ratios between 25 – 30 lead to maximum span lengths of 5 to 5.5 m for systems commonly used in practise (single, two or three span beams; when calculating as simplified 1D system). To avoid uneconomic dimensions, this fact should be considered when thinking about the room layouts of a residential project. Figure 8 shows two typical floor slab systems in CLT.

a)



b)

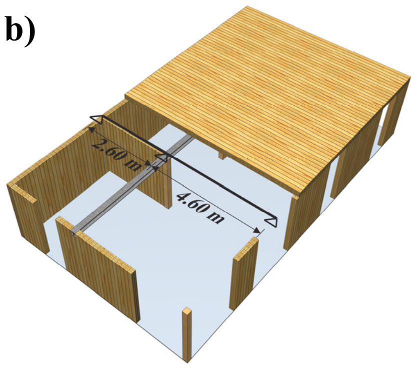


Figure 8: *Residential floor slab systems in CLT; a) Single span system (t_{CLT} = 198 mm) with two outer bearing walls; b) Two span system (t_{CLT} = 160 mm) with two outer and one inner bearing wall [7]*

Of course, the two span system given in Figure 8b has a structural advantage leading to a more economic dimension if compared to case a). However, it should not be forgotten, that the inner bearing wall has a two-sided fire exposure in this case. Often, this turns out being the decisive design criteria of the CLT wall leading to increasing costs as consequence of (a) a double or triple planking with gypsum boards or (b) an element thickness with roughly twice the dimension as it results from "cold" design.

In addition to the proposed use of optimised span lengths, the chosen structural floor system should not strongly vary in its type and dimensions in the frame of one project. In contrast to more flexible in-situ RFC solutions, CLT always is a prefabricated product and significantly benefits from uniform conditions (lay-up and thickness).

4.2 WALLS

When analysing a common residential multi-storey building in solid timber construction, the proportion of CLT wall and floor elements is roughly equal (cf. [13]). Consequently, the arrangement of the load bearing walls significantly influences the efficiency when building with CLT. Figure 9 represents a proposed three-storey wall elevation with two essential principles to be pointed out:

- To avoid waste of resources as consequence of large offcuts, all elements have a full storey height and no openings. Windows and balcony doors are also room high or partially combined with secondary components. With regard to maximum dimensions producible ($l_{max} \approx 16$ m), another alternative would be the arrangement of continuous CLT wall elements over the whole building height.
- The positioning of the walls on top of each not only simplifies their design and decreases their stress rate but also ensures that horizontal loads (wind and especially earthquake, see EN 1998-1:2011, section 4 [14]) are directly transmitted to the foundations.

Thus, the loads the connections have to bear are also significantly reduced.

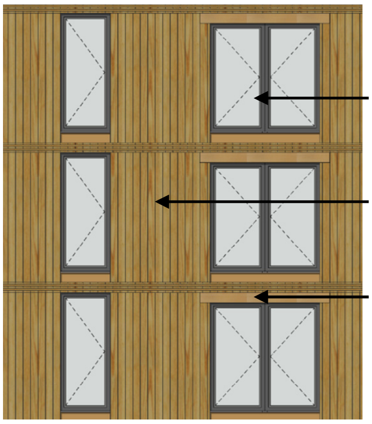


Figure 9: *Proposed arrangement of wall elements in elevation [7]*

4.3 CONNECTIONS

Equal to (or better: copied from) buildings in timber lightweight construction technique, angle brackets and – in cases where high uplift forces have to be transmitted – hold-downs are used to connect CLT wall and floor elements together. The disadvantages of these systems are (a) their relatively low bearing resistances and (b) the eccentric arrangement, leading to a multiplicity of fasteners in critical building parts. Consequently, the connection system shown in Figure 10 and consisting of inclined positioned self-tapping screws (floor to wall) and a T-shaped steel plate with self-drilling dowels (wall to floor) serves as high load bearing alternative, especially for connecting the elements in the first storeys. With regard to the higher costs of such prototype systems, there's a certain need of developing simple system connectors suitable for CLT constructions.

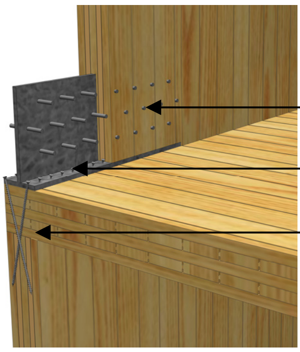


Figure 10: *Dowel-type connection with steel plate in between the wall element [7]*

5 CONCLUSIONS

Based on both topics "internal and external protection of moisture ingress" and "efficient structural systems for CLT floors, walls and connections", especially focused in our paper, we summarise and conclude:

- For multi-storey residential buildings, erected as solid timber constructions with CLT, the flat roof, the balcony construction and the wall assembly itself are identified as the critical parts of the building envelope influencing the durability of the construction.
- As discussed in section 2, CLT flat roof assemblies should provide an inclined back ventilation zone accessibly for maintenance and serving as second protection against moisture ingress.
- To enable the possibility for replacement due to different lifetimes as well as to avoid uncontrolled air and moisture transfer into the bearing structure, the balcony system should always be installed as renewable secondary construction in steel or timber.
- A thermal façade system suitable for remarkable vertical CLT wall deflections and tested regarding the interaction of its components with CLT as base coat should be used instead of ETIC systems developed for mineral constructions.
- Details concerning building services, especially ones, which include pipe systems containing water, have to be solved for a bearing structure losing its performance in case of moisture ingress. The proposals made in this paper are only seen as begin of a development in that direction.
- CLT is a prefabricated product. Thus, uniform and material-optimised structural systems (vertical and horizontal) maximize its efficiency and avoid waste of resources.
- For high stressed joints, centrically situated dowel-type connections should be used instead of numerous angle brackets or hold-downs.

Cross-laminated timber is a powerful, efficient building material and – if applied in a right way – a realistic alternative to reinforced concrete for multi-storey residential buildings. As consequence of its mechanical and physical performance, especially regarding moisture ingress, new solutions increasing the building quality and its durability have to be found or improved, especially for internal and external critical building zones discussed in this paper. More than for other building materials, an interdisciplinary planning process from the early stage of a housing project is thus necessary.

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