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Very Tall Wooden Buildings with Cross Laminated Timber

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Abstract

Cross Laminated Timber (CLT, XLAM) is a product extremely well suited for multi-storey buildings because of its versatility. With lengths up to 16 meters and the possibility of extending with mechanical joints or glued connections, widths of up to 2.5 meters depending on manufacturer and thicknesses up to 500 mm, almost any necessary shape can be found on the market today. Developments are still going on rapidly and new possibilities and new applications far from being exhausted. One such new possibility is the use of CLT elements in a combination with a concrete core and structural outriggers in very high buildings, a ´wood-concrete skyscraper´. CLT has already been shown to be very efficient in multi-storey buildings up to 10 storeys. In this paper, an analysis is given of how a concrete core and CLT walls can be used to design very tall buildings in the range of up to 150 meters, but for more than 80% made of timber products. Timber can become an alternative in rapidly expanding cities, where there is a need for high apartment buildings. The building layout uses outriggers at certain intervals, integrated tension cables and CLT structural wall elements in the facades. The design makes optimal use of the advantages of light-weight building elements with comparable structural performance as traditional concrete elements. Savings during the erection stage in terms of money and time are highlighted as well as the CO_2 emissions of such a building in comparison with concrete. A concept of the building has been analysed for the location of Shanghai according to the Chinese wind load specifications.

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1. Introduction

Cross Laminated Timber (CLT) is a product extremely well suited for multi-storey buildings because of its versatility. With lengths up to 16 meters and the possibility of extending with mechanical joints or glued connections, widths of up to 2.5 meters depending on manufacturer and thicknesses of up to 500 mm, almost any necessary shape can be found on the market today. Developments are still going on rapidly and new possibilities and new applications far from being exhausted. One such new possibility is the use of CLT elements in a combination with concrete in very high buildings, a wood-concrete skyscraper. CLT has been shown to be very efficient in multi-storey buildings with earthquake tests being performed on 3 and 7 storey buildings in Japan (Ceccotti, 2008), (Ceccotti et al. 2009), and on special connections between panels (Sandhaas et al. 2009). In the latter it was shown that panels with only three layers have a comparable good performance against cyclic loading (earthquakes) as five layer panels, showing the potential of CLT in high buildings with horizontal loading situations as most important. As far is known, the highest building created so far with cross laminated timber elements is Murray Grove in London, a nine storey building where also the elevator shafts are made of CLT (Yates et al. 2008), (Anon.). The development of CLT, the realized structures with up to 9 storeys and the good performance under severe loading conditions has lead to the development of a wood-concrete skyscraper concept for very tall buildings. This concept was presented by Van de Kuilen et al. (2010). In this paper some of the important aspects are highlighted as well as implications of such a building from a sustainability point of view.

2. Structural Design Concept of A Wood-Concrete Skyscraper

The 'wood-concrete' skyscraper uses a mixture of building materials for its structural system, but the majority of the load bearing structural elements are made of cross laminated timber or CLT. The concept makes use of integrated steel tension bars. With these integrated steel bars, large numbers of fasteners can be avoided that otherwise would be needed against uplift loads, especially in the case of high winds or earthquakes. CLT is introduced in this chapter as well as the construction system. Some preliminary design calculation have been presented in Van de Kuilen et al. (2010).

2.1 Cross laminated timber

Cross Laminated Timber (CLT) has been developed around 15 years ago in Central Europe. Basically, it consists of crosswise glued layers of timber boards as shown in figure 1. Layering crosswise brings advantages in terms of load bearing capacity in two directions, increased shear capacity in the plane of the elements, and the elimination of shrinkage and swelling in the plane as a result of humidity variations. Other advantages are a high level of prefabrication where openings for doors and windows can already be included in the factory, easy fastening of the elements on site and a low weight as compared to traditionally used concrete. Usually, the panels are produced with 3, 5, 7 layers or more layers which generally is limited for technical reasons to approximately 500mm. Most are characterized by a fixed length of up to 16-20 meters and width of up to 3 meters. Width of single wood strips usually varies between 80 and 240mm, when thickness between 10 and 40mm.
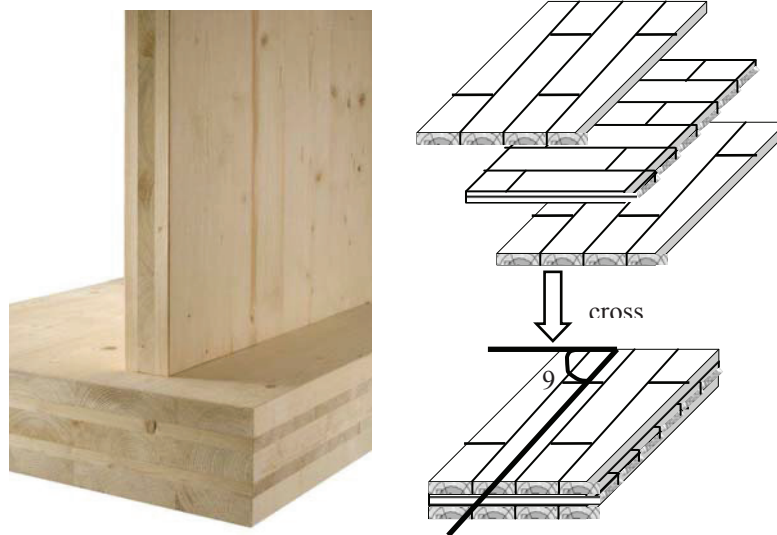
Figure 1: Picture and lay-up of cross laminated timber

2.2 Structural system

The basic structural system is given in figures 2 and 3. The rigid outrigger storeys provide:

- stability to the core;
- a lever arm for the global bending moments;
- a division between timber sections for fire safety;
- allow for building services (equipment);
- shelter spaces in case of emergencies.

A different building concept is possible when the outriggers have sufficient high rigidity that they might serve as a basis for a timber infill building that stands in its own, independent of the megastructure. The outriggers can be made of concrete, steel or possibly even of CLT elements, which is subject of further study. It is assumed that CLT for buildings with predominantly compression stresses can be stratified, so a large portion of the timber is loaded in the grain direction, while a smaller portion is glued crosswise. If it is assumed that 2/3 of the panel has the boards loaded parallel to the grain, an effective value of MoE can be taken as 8000 N/mm^2. Concrete is homogeneous structure material, and the modulus of elasticity of (cracked) concrete assumed to be 15.000N/mm² for the preliminary design calculation.

2.3 Preliminary design

The wood-concrete skyscraper seems to be a feasible alternative for apartment buildings (Van de Kuilen et al, 2010). In order to check the feasability, a simple rectangular building has been designed with more than 40 storeys and a total height of 150 metres with outrigger storeys located at the 10th, 20th and 30th storey, with outer walls of CLT. CLT serves extremely well in taking up compression loads, but on the tension side of the building quite a number of fasteners would be needed. To avoid this, steel tension bars are integrated in the CLT panels, see Figure 4. Parameters for the preliminary design of the building deal with the shear and bending stiffness of the elements.
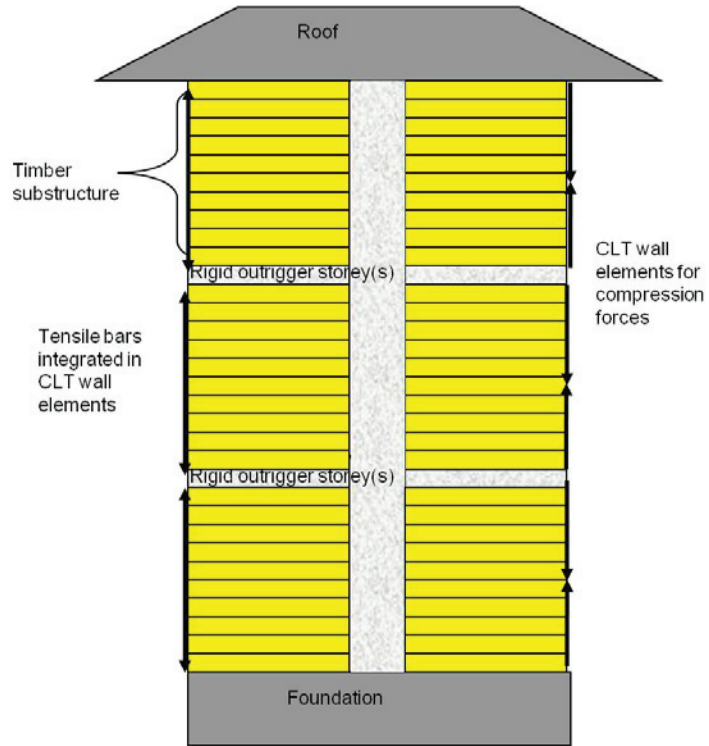
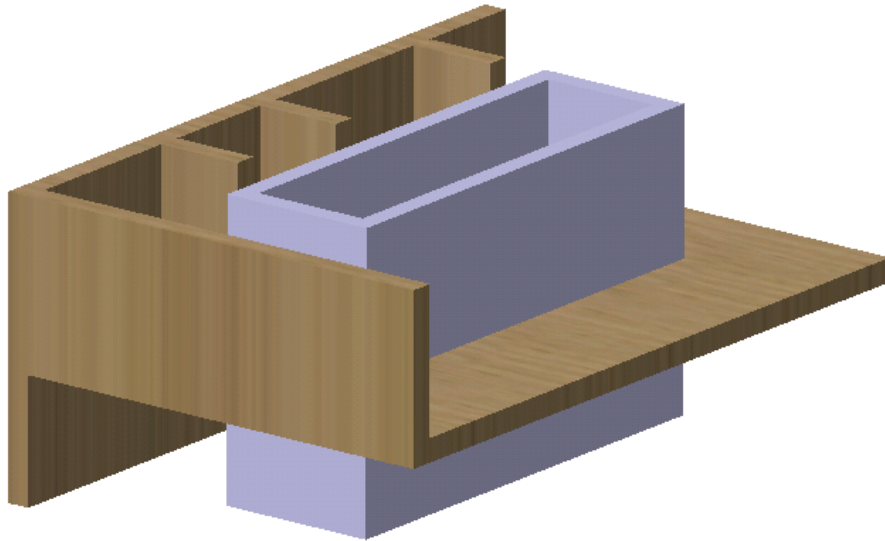Figure 2: Concept of a wood based high rise building with outriggers

Figure 3: Image of a cross section with concrete core and CLT floors and walls.
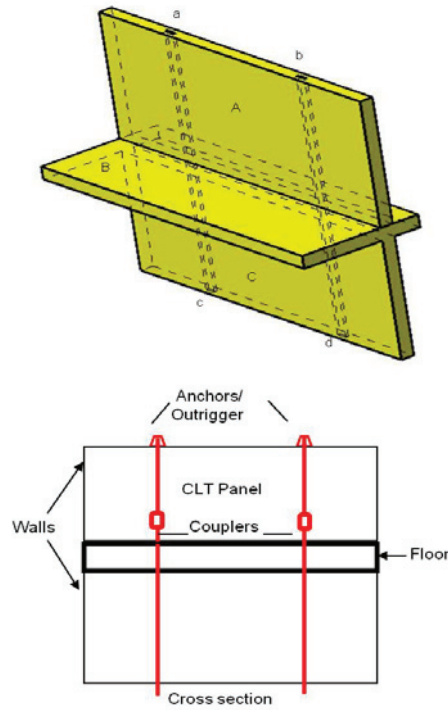
Figure 4: Concept of a Wall-Floor-Wall connection of CLT with integrated tension bars

Typically, the following parameters need to be known:

EI   Bending stiffness of the load carrying walls for bending;

GA   Shear stiffness of the wall elements that contribute to limit the shear deformation;

EAe_i^2 Contribution of wall elements to the bending stiffness, having an eccentricity e_i to the neutral axis.

Especially with regard to the shear modulus G a large difference is observed between concrete and CLT with a ratio of approximately 15 to 1: namely 12000 N/mm^2 for concrete and 750 N/mm^2 for timber. The building has two major bending stiffnesses, one is the stiffness of the floors with mainly CLT elements and concrete core, and the other one is the stiffness of the outrigger floors, here presumed to be predominantly made of concrete. The preliminary analysis is performed on the building with a simple lay-out where the central core is located in the centre of the building. The core rectangular is taken 8 x 21 m, building rectangular is taken 25 x 35 m, see Figure 5. Wall thicknesses were assumed to 0.25 m for concrete and 0.35m for CLT.

The average bending stiffness of the building can be expressed as [Hoenderkamp et al, 2009]:

$$(EI)_{Avg} = \frac{a(EI)_{core+CLT} + b(EI)_{outrigger}}{a+b} \tag{2}$$

where *a* is the number of CLT and concrete core stories, *b* is number of outrigger storeys.
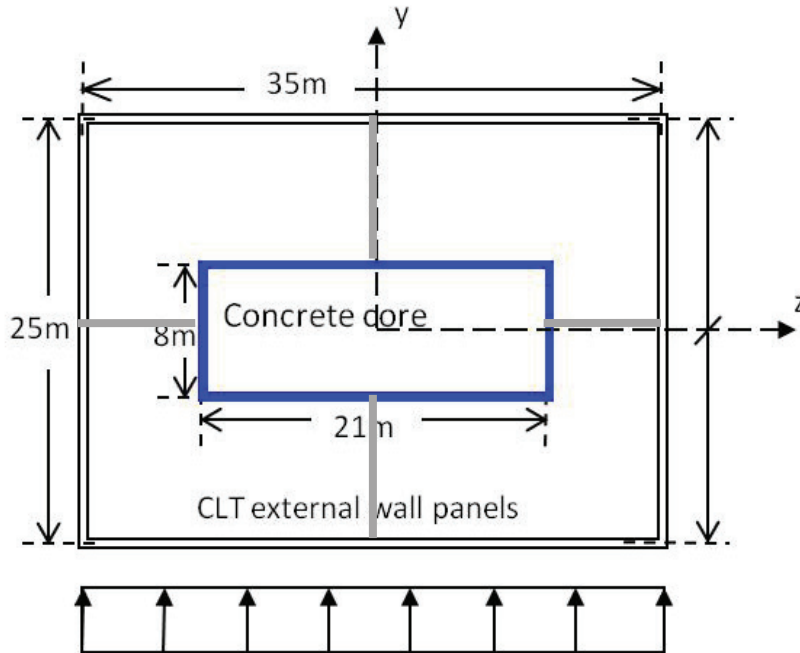

Figure 5: Simplified example of timber high rise building with concrete core

This gives for the floor made of wood with concrete core the following bending stiffness:

$EI_{clt,c} = EI_{CLT} + EI_c = 3.71E^{10} + 1.34E^9 = 3.84E^{10}$ kNm^2,

and for the outrigger floor (all walls made of concrete):

$EI_{clt,c} = EI_C + EI_c = 5.0E^{10} + 1.34E^9 = 5.13E^{10}$ kNm^2

This leads to an average bending stiffness of the building of $3.93E^{10}$ kNm^2, with 40 timber floors and 3 concrete outriggers. The grey walls in Figure 5 can be made of CLT as well and take up the shear forces that develope along the vertical axis between the concrete core and the timber outer wall. For the bending and shear sway of the building, the maximum displacement at the top of the building can be determined as follows:

$$\delta_b = \frac{q_w H^4}{8EI} \text{ and for shear } \delta_s = \frac{q_w H^2}{2GA} \tag{3}$$

The wind load is modelled according to the Chinese design code for Shanghai and for the preliminary design has been taken as 2.8 kN/m^2. The maximum bending moment as a result of the wind load is determined at $M_w = 535 \cdot 10^6$ kNm. This bending moment is taken up by two bending ´beams´ (the core and the CLT frame) and leads to small compression stresses on the right side of the building (see figure 3) of around 1.4 N/mm^2, presuming this part of the timber building is designed for such

compression forces. The assumed wall thickness of CLT of 350 mm and of concrete of 250 can be verified at this stage. Similar stresses in tension can be found on the left side, if the timber infill building is connected to the outrigger in such a way that tension stresses can indeed develop. However, since this would require large numbers of heavy fasteners, the tension bars shall take up these loads. The number of bars required to take up the tension forces are determined and given in table 1.

Table 1: Number of integrated steel tension bars (rounded to nearest even number)

Level	$F_{w,v,z,d}$ (kN)	Wide side ($\varnothing$=40mm)	$F_{w,v,y,d}$ (kN)	Narrow side $\varnothing$=40mm
4th. region	-5261	[-]	-6590	[-]
3rd. region	1724	2	-3026	[-]
2nd. region	11490	12	1957	2
1st. region	21888	22	7262	8

The average bending stiffness can be used when the timber on the tension side of the building is cooperating in the building stiffness. If this is not the case, the stiffness becomes less and more deformation may be expected. In that case, the steel tension bars could be used for prestressing the timber, increasing the tension stiffness. The calculated bending displacement at the top of the building becomes around 160 mm with a wind load of 2.8 kN/m^2. The sway index for bending is calculated as $\delta/H \approx 1/950$. For shear, a defomation at the top of around 40 mm is estimated. As a result, the total deformation at the top is in the order of magnitude of 200 mm or $\delta/H \approx 1/770$. This is below the generally required limit of $H/500 \approx 300$ mm.

3. Building Process

Due to the high level of prefabrication, the building can be erected rapidly. Apart from the outrigger structures, repetition is high and the elements are light in comparison to traditional concrete. This light weight brings considerable advantages during the construction stage. For the Murray Grove building, Yates et al. (2008) estimated a 17 weeks time saving. For tall buildings, the number of cranes and crane times may become important from an economic point of view. When calculating the costs of tower cranes a monthly rent of at least 6.000 USD can be expected, so rental savings can be considerable over the construction time. As a comparison, crane times are compared based on the transportation time of materials to the floors that need to be constructed. The time needed for construction is then partly governed by the speed at which elements are brought up to the working floor. Time savings up to one-third can be achieved on the pure hoisting time for this building.

4. Environmental Impact

The exchange of concrete by a sustainable material gives considerable environmental advantages. The majority of the building made with wood, requires less energy during manufacturing of the elements and during the construction stage. In addition, wood is the only building material with a negative CO_2 balance, i.e. it stores CO_2. Each cubic metre of wood sequestrates an average of 0.8 – 0.9 tonnes CO_2. Using wood as a substitution for other materials it saves an additional 1.1 tonnes of CO_2 that would have been emitted when using concrete. This results in a total saving of approximately 2 tonnes CO_2. With the dimensions used in the example, the building uses around 0.75m³ of CLT panel per m^2 of apartment. This building is a 43 storey 142m high residential building with a floor dimensions of 35m*25m, in which cross laminated timber panels are used as mainly construction material to erect 40 storeys. A total of around 26300m³ of wood is required, avoiding around 50,000 Tons CO_2 emissions. This is equivalent to what 33 thousand cars emit in one year.

5.   Conclusions and Further Studies

The feasability of a wood-concrete skyscraper has been analysed and shown to be possible. The number of integrated steel bars needed to take up the tensile forces on the tension side of the building seem reasonable. The next step in the process will be a more advanced design, analysing the shear transfer and the shear walls between the concrete core and the timber outer walls. Furthemore, the CLT wall thickness was initially estimated at 350 mm, but this seems high with respect to the calculated stresses and defomations. More general, aspects as fire safety and earthquake performance shall be studied in the future.

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