WOOD CONCRETE SKYSCRAPERS

Jan-Willem van de Kuilen¹, Ario Ceccotti², Zhouyan Xia³, Minjuan He⁴, Shuo Li⁵

ABSTRACT: Multi-storey buildings in timber have gained increased interest with the development of cross laminated timber products. A wide variety of CLT-elements is currently on the market, most characterized by a fixed width and lengths of up to 16-20 meters. Thickness generally is limited for technical reasons to approximately 350 mm. Even though no product standard is available yet, multi-storey buildings have been realized with CLT in a number of countries, showing the potential of the product. A multi-storey building with seven storeys was tested for earthquake resistance by CNR-Ivalsa in 2007 in Japan. A further development in this field is the development of mixed structures, such as wood-concrete skyscrapers. Depending on the conditions, very tall buildings can be built, mainly made out of timber. With the right combination of other materials such as concrete, skyscrapers can be designed using a system of outriggers and tensile elements in the facade with a combination of CLT-panels. In this paper, some basic concepts are presented, as well as a number of advantages using such combinations, including positive effects on crane times and building economics. The main market of such buildings is thought to be in rapid developing countries such as China and India, where cities show rapid growth and demand for environmentally friendly housing is on the rise.

KEYWORDS: Cross Laminated Timber, Multi-storey building, Outriggerse, Skyscrapers, Crane times.

1 INTRODUCTION

Cross Laminated Timber 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 350 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 already been shown to be very efficient in multi-storey buildings with earthquake tests being performed on 3 and 7 storey buildings in Japan on elements against push-over [1], [2], and on special connections between panels [3]. 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 [4], [5].

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Figure 1: Murray Grove during the erection stage (photo courtesy of KLH, www.klh.at)

The high load-bearing capacity of cross laminated timber, both in plane as well as out of plane, makes it suitable for even higher buildings, but for timber alone a limit in the number of storeys can be expected.
somewhere between 15 and 20 storeys, even though in recent years the limit was thought to be around 10 storeys [6]. For multi-storey buildings with such a high number of storeys, fire safety may become the main governing parameter, whereas earthquake design and horizontal wind loads may become governing for slender and/or tall buildings. Slender and tall buildings are currently required in many areas in the world where populations are migrating in increased numbers to big cities. This is the case in countries like China and India, but also countries as Brazil, Egypt, Pakistan and many others have increased pressure for developing housing alternatives that shall be cheap, fast built and environmentally friendly. The word ‘megacities’ is no longer applicable since such large cities become part of larger regions with clusters of cities. For such ‘megaregions’ or ‘megalopolis’ areas, the concept of wood-concrete skyscrapers may be an alternative. The concept is based on the use of outriggers at certain intervals, which support wooden multi-storey infill buildings. The infill buildings or substructures are multi-storey wood buildings that may have around 10 to 15 storeys themselves. Sustainable building materials can thus increase their share also in tall buildings.

2 SKYSCRAPERS AND THE OUTRIGGER PRINCIPLE

The principle of using outriggers in skyscrapers has been applied in a number of well known buildings around the world. The construction is based on a core in which elevators, stairs etc. are brought together and which provides resistance mainly against shear, and partly against bending.

Two examples are given: the former Philips headquarter building in Eindhoven (Figure 2) in the Netherlands and the Yin Mao tower in Shanghai, China (Figure 3). The Philips building has one large outrigger on the top, and the floors are hanging on a tension structure.

The Yin Mao Tower has a hexagonal central concrete core and on each facade two heavy steel-concrete columns. Outriggers are located on the 24th, 51st, and the 87th floor. The outriggers are steel trusses which is efficient for office buildings, but for residential buildings, concrete could also be used. The outriggers themselves are two storeys high. For the concept and building types discussed here, it is assumed that one storey for the outrigger is sufficient.

Taranath [7],[8] analysed outrigger systems and demonstrated that the optimum location for a single outrigger is approximately in the middle height of the building for minimizing the roof lateral displacement under wind load. An outrigger placed at top, acting as a cap or hat wall, is about 50% less efficient than that placed at middle height. However, in many practical situations, it may be more permissible to locate the outrigger at the building’s top. For a tall building with multiple-rouiggers, generally, the optimum performance of n-ouiggers should be placed at 1/n+1, 2/n+1, up to the n/n+1 height locations, i.e. arranged evenly at the height of whole building. Each additional level of outriggers increase the lateral stiffness, up to four outrigger levels may be used in very tall buildings. A structure with outriggers will have 30 to 40 percent less overturning moment in the core compared to a free cantilever in addition to having less drift. The decreased lateral displacement and overturning moment of the building will also decrease the cost of its columns and its foundation.

With outrigger systems, the flexural capacity of the building increases effectively, while the shear capacity cannot be increased as it has to be carried mainly by the core.

Figure 2: Former Philips headquarters building with outrigger on the top, Eindhoven, NL.

Figure 3: Cross section of Yin Mao tower in Shanghai, central core, outrigger and columns
The function of the outriggers can be listed as:

1. Providing stability to the core;
2. Providing a level arm for the global bending moments;
3. Providing a division between timber sections for fire safety;
4. Allowing for building services (equipment);
5. Shelter spaces in case of emergencies.

Most of the buildings with outrigger systems have office spaces located around a central core. The facades are generally constructed using single columns. Such a concept is also applicable for apartment buildings using wood-based elements as infill. These elements can then be easily made of traditional wood-frame panels.

However, another option using outrigger systems for apartment buildings is to make the outer shell (the facades) of load carrying structural wall elements, preferably CLT because of the high volume of wood available for compression forces. On the other side of the building where tension forces prevail, two options are available. Either the CLT elements take up the tensile forces by means of anchors fixed to the outriggers, or the tension forces are taken up by integrated steel tension bars. The CLT elements contain spaces where the steel bars are placed and the panels are vertically connected through consecutive floors, see figure 4. Such steel tension bars are commonly available in the construction industry and available in diameters of up to 42 mm. The available length of such bars is up to 16 meters, so a coupling is needed around every fourth storey.

Apart from structural safety, another important design aspect for tall buildings is comfort, generally taken into account by limiting horizontal drift, interstorey drift and vibrations. Horizontal drift should typically be restricted to around 1/500 of the height of the building or smaller. Bending and shear stiffness are thus important parameter as well. The principle is shown in figure 5. The outrigger concept can be applied in one or two main building axes. If only one axis is chosen, the effect of differential deformations due to different axial stiffness values needs to be considered in the design. Especially when a platform frame concept is used for the timber substructure, compression deformations perpendicular to the grain need to be considered.

The principle of a wood-concrete skyscraper with load-bearing wall elements in compression and integrated tension bars is shown in Figure 5.
A system with diagonal bars is also possible when bending moments are low or for not too tall buildings. In that case, the CLT wall panels can be provided with a layer with 45° board angle as to provide for the spaces needed for the steel tension bars. A combination is also an option where the upper element is constructed of a system with bars under an angle for the highest timber substructure. For very large structures, it is also possible to create multi-storey timber substructures that are independent from the main structure. In such a case, the external horizontal loads are taken up by separate elements independent of the timber infill. Such structures are however not considered here.

3 SHANGHAI EXAMPLE

Shanghai with over 20 million people is one of the largest modern cities in China, located in the middle of China's east coast at sea level. A typical view of high rise apartment buildings in Shanghai is shown in Figure 6.

Shanghai has a humid subtropical climate. In winter, cold north wind coming from Siberia can cause one or two days snowfall per year. In summer, the city is susceptible to typhoons. An aerial view of Shanghai is given in Figure 6, showing the huge amount of high rise residential buildings. Although no typhoon in recent years has caused great damage, the high wind speed is still one of the main design governing parameters causing horizontal deflection and vibration of tall buildings.

The building plan of a typical multi-storey apartment building is given in Figure 7. Each storey contains comprises four apartments having around 80 m² of living space each. Thick black lines are considered to be load bearing elements. Such an apartment building may have around 30 to 40 storeys, giving a total height of around 100 to 140 meters, assuming a 3.3 meter storey height for residential construction. An example case is now considered for the wood concrete skyscraper concept.

3.1 WIND LOAD

The highest recorded date of wind force is in the range of 10 to 11 with a high speed about 30 m/s. Typhoons, which seldom steps inside the west region of 120° eastern longitude, will rarely land in Shanghai because of Shanghai's location of 31°14'N 121°30'E, but cause influence as windstorm of wind force 8-9 class with wind speeds at about 17 m/s – 24 m/s. Reference basic wind pressure in Shanghai is 0.4 kN/m² on 10-year return period, 0.55 kN/m² on 50-year return and 0.6 kN/m² on 100-year return. On the basis of this pressure, actual wind load on the facade is calculated using GB 50009 of China:

\[ w_k = \beta z \mu z w_0 \]

in which:

- \( w_k \) = effective design pressure
- \( w_0 \) = reference wind pressure
- \( \mu_z \) = exposure factor allowing for the height and location of the structure
- \( \mu_s \) = aerodynamic shape factor or pressure coefficient
- \( \beta_z \) = effective gust effect factor

The exposure factor \( \mu_z \) takes into account the height of the building and the terrain roughness, i.e. if the building is surrounded by other building and the type of terrain. As the timber-concrete building is design to be located in Shanghai, the exposure factor is assumed as type D according to GB 50009, for large city-centres with heavy concentrations of tall buildings. The shape factor is the external pressure coefficient averaged over the area of the surface considered, influenced by the shape of the building, the wind direction, and the profile of profile of the wind velocity. For a rectangle building, the value of \( \mu_s \) in windward is 0.8, while in leeward is -0.6. Thus for the design of the lateral load resisting, global shape factor \( \mu_s \) of the design of timber-concrete building will be 1.4. The factor \( \beta_z \) is a gust effect factor taking in account the dynamic response of the building. As a consequence, wind load pressure for normal buildings is around \( 1.5 \times (0.8 + 0.6) \times 0.55 = 1.2 \text{ kN/m}^2 \). For tall buildings discussed here, this value increases to around \( 2.8 \text{ kN/m}^2 \) for a location like Shanghai.

The timber-concrete building to be design is a concept with three outriggers, 43 stories and about 145m high, 35m with and a depth of 25m. Such a building corresponds to development trend of normal residential buildings in centre of Shanghai which nowadays usually reach 30 to 40 stories. Building slenderness is around 1:6.

3.2 STRUCTURAL ASPECTS

For the example it is assumed that the circumference of the storey is made of load bearing walls, as well as a central core. The building is shaped with three outriggers at the 10th, 20th and 30th storey respectively.
Parameters for the preliminary design of such a building deal with the shear and bending stiffness of the elements. 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;
- **EAEe**^2**: Contribution of wall elements to the bending stiffness, having an eccentricity e, to the neutral axis.

Especially with regard to the value of G a large difference is observed between concrete and CLT with a ratio of approximately 15 to 1: namely 12,000 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 mainly made of concrete. The preliminary analysis is performed on the building with lay-out and cross sections as shown in figure 8. For this example, the central core is located in the centre of the building, so the stiffness parameter **EAEe**^2 is set to zero. This is normally not the case, but only slightly complicates the preliminary design. The average stiffness of this building can be expressed as follows [11]:

\[
(EI)_{avg} = \frac{a(EI)_{core, CLT} + b(EI)_{outrigger}}{a + b} \tag{2}
\]

where \(a\) is the number of CLT and concrete core stories, \(b\) is number of (concrete) outrigger storeys. \(E\) is modulus of elasticity and here it is assumed that CLT for buildings with preliminary compression stresses can be stratified, so a large portion of the timber is 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 can be taken as 8000 N/mm^2. Concrete is homogeneous structure material, and the modulus of elasticity of (cracked) concrete assumed to be 15,000 N/mm^2 for this example. This gives for the floor made of wood with concrete core the following bending stiffness:

\[
EI_{clt,c} = EI_{CLT} + EI_{c} = 3.71 \times 10^{10} + 1.34 \times 10^{9} = 3.84 \times 10^{10} \text{ kNm}^2,
\]

and for the outrigger floor:

\[
EI_{clt,c} = EI_{c} + EI_{e} = 5.0 \times 10^{10} + 1.34 \times 10^{9} = 5.13 \times 10^{10} \text{ kNm}^2.
\]
This leads to an average bending stiffness of the building using equation (2) of $3.93 \times 10^{10}$ kNm², with 40 timber floors and 3 concrete outriggers.

For the bending sway of the building, the maximum displacement at the top of the building can be determined as follows:

$$\delta = \frac{q \cdot H^4}{8EI}$$

in which:
- $q_w$ = wind load (kN/m²);
- $H$ = building height (m);
- $EI$ = building bending stiffness (kNm²).
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. The calculated bending displacement at the top of the building becomes around 160 mm with a wind load of 2.8 kN/m². The sway index for bending is calculated as $\delta/H = 1/950$.

For the shear deformation the following equation can be used:

$$\delta = \frac{qH^2}{2GA}$$

which, for the building of figure 8, gives a shear deformation at the top of around 40 mm. As a result, the total deformation at the top is in the order of magnitude of 200 mm or $\delta/H = 1/770$. This is below the generally required limit of $H/500 \approx 300$ mm.

The positive influence of the outriggers on the deformation of the building has so far not be taken into account. The bending deflection decreases, because the bending deformation of the core is restrained. As a consequence, the deflection $w$ at the top of the building is restrained by the three outriggers and is determined by the following equation [12]:

$$\delta_{\text{max}} = \frac{wH^2}{8EI} - \frac{1}{ET} \left[ M_i (H^2 - x_i^2) + M_i (H^2 - x_i^2) + M_i (H^2 - x_i^2) \right]$$

The second part of this equation is analysis of further study since it depends on the bending moments $M_i$ at the outrigger.

The maximum bending moment as a result of the wind load is determined at $M_w = 535 \cdot 10^6$ kNm. The wind load is modelled according to the Chinese design code, giving a higher wind load on the upper storeys than on the lower. 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 5) of around 1.4 N/mm², 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. If this is not the case, then the steel tension bars need to take up the tension forces. In this example, (lay-out of figure 8), a total of 26 bars Ø 30 mm would be sufficient with regard to strength.

4 CRANE TIMES

One of the advantages of using wood as major structural element is the high level of prefabrication that can be achieved and the light weight in comparison to concrete. This light weight brings considerable advantages during the construction stage. Especially when tall buildings need to be built, number of cranes and crane times may become important from an economic point of view. As a comparison, crane times are compared based on the transportation time of materials to the floors that need to be constructed. A typical crane type used for high rise apartment building construction is a tower crane. The capacity of such a crane is basically based on the weight that needs to be transported to the $i$-th storey. The time needed for construction is then partly governed by the speed at which elements are brought up to the working floor. An example calculation is based on a crane with hoisting capacity-speed as given in figure 9.

The high speed of building gives considerable financial advantages. For the Murray Grove building, Yates et al. [4] estimated a 17 weeks time saving. When calculating the costs of tower cranes a monthly rent of at least 6.000 USD can be expected for tall buildings, so rental savings can be considerable over the construction time.

![Figure 9: Crane speed as a function of jib, load and speed, Liebherr Cranes](image)
The hoisting time, calculated as the accumulated vertical transportation time, is about one-third of that of prefabricated concrete elements. Since weight counts linearly, it also holds for in-situ concrete if not pumped. The fact that the crane has a larger reach with the CLT building elements weighing roughly 30% of that of concrete, leads to other advantages. This leads to fewer cranes needed on a single building site. These advantages are however not directly quantifiable as they depend on the lay-out of the building site (crane location(s)) as well as the building floor plan.

As calculated before, when all the other conditions keep the same, one floor cross-laminated timber boards only need 8 times to be carried up to a certain level. Therefore, compared to concrete walls, only one third transportation’s time (approximately 22.6 hours) is required for the cross-laminated timber storey for a high-rise building. In respect of panels’ craning, much more time can be saved by using CLT elements than by using concrete members when a building rises higher.

<table>
<thead>
<tr>
<th>Storey</th>
<th>Height (m)</th>
<th>Hoisting time concrete (min)</th>
<th>Hoisting time CLT panels (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>9.9</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>13.2</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
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<td>24</td>
<td>8</td>
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<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>36</td>
<td>118.8</td>
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<td>38</td>
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<tr>
<td>39</td>
<td>128.7</td>
<td>185</td>
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<tr>
<td>40</td>
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</tr>
<tr>
<td>Total</td>
<td></td>
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<td>1351</td>
</tr>
</tbody>
</table>

The gain in construction time is considerable even though here only hoisting time is considered. It can be expected that more gains are obtained because of faster mounting on site. At the same time, the construction of the outriggers at certain intervals may slow down the construction speed because of interrupted repetition, but experienced contractors should be able to realize at least two storeys per week if not more.

5 CONCLUSIONS AND OUTLOOK

A concept for very high buildings is presented that can be constructed with large amounts of prefabricated timber elements. Typical design aspects and mechanical parameters are identified as well as advantages during the construction stage. Structural details are in the development process, especially with regard to the connections between steel bars and the outriggers as well as integration within the CLT elements. The connections between timber building and outriggers and core are essential in the structural design and calculation process. There locations and stiffnesses determine the force flow inside the building, the overall stiffness of the building and the amount of steel bars needed to take up the tensile forces. With the calculated example it seems that the construction principle is feasible. But many aspects need still to be analysed. If the core position changes, the structural analysis remains similar, but eccentricities have to be taken into account that may lead to higher bending stresses and possibly torsion effects. Similarly, in this example fixed thicknesses for both timber and concrete have been taken, but the stresses indicate that timber thickness might be reduced.

Another field of research and development is the fire safety of the timber infill buildings. Until now, in many countries it is not possible to build higher than 5 to 6 storeys with timber. Especially in this case, the fire safety considerations for multi-storey buildings in timber need to be combined with fire safety concepts used nowadays in the analysis of skyscrapers.

Environmental impact is another advantage of using CLT prefab elements instead of concrete. Not only during production, also during the service life of the building this allows for a considerable amount of carbon storage, not being possible with other building materials. In addition, at the end of life, the CLT elements can easily be adapted and reused or, if no other option is possible, used for energy generation.

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