Smart tall wooden buildings with Cross Laminated Timber

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ABSTRACT

Tall buildings are key structures in the future urbanization of the world. The population growth and urbanization are projected to add 2.5 billion people to the world's urban population by 2050. The CO_2 emissions, partially caused by the building industry in large cities are alarming. It is the task of the building industry to house the urban population by designing more sustainable high-rise structures. Wood can partially be the answer towards more sustainable high-rise buildings. Since the introduction of Cross Laminated Timber it is possible to make large spans with wood, opening up the opportunity to make high rise structures with wood. Research proves that it is possible to build a building which is higher than 100 meters completely out of wood. Which can reduce the CO_2 emission with 70%. The effect will be even larger if the CO_2 storage capacity of wood is taken into account. An interesting development, however there are more possibilities which seem to be neglected by the CLT industry. CLT is treated as prefabricated concrete, timber however, can be used to make much more advanced elements in a simple way, with better qualities regarding comfort and sustainability. Making wooden buildings with efficient material design kept in mind can really make a difference regarding sustainability. There is a need for alternative tall wooden structures which do not focus on building solely with CLT, but with various products and materials working together to form a convincing sustainable solution.

Keywords: High-rise timber buildings, wooden skyscrapers, CLT, Cross Laminated Timber, Material Efficiency

THE NEED FOR TALL WOODEN BUILDINGS

Tall buildings are key structures in the future urbanization of the world. The population growth and urbanization are projected to add 2.5 billion people to the world's urban population by 2050 (United Nations, 2014). The prospect is that 90% of this increase takes place in Asia and Africa. This increase of population means the need for tall buildings in the near future. The conventional construction materials to build tall buildings are concrete and steel. Materials that have proven their usability, but concrete and steel are also materials with very high energy and very high greenhouse gas emissions in their process. Michael Green, a Vancouver based architect suggests that the answer to climate change and urbanization lies partly within constructing wooden buildings (Green, 2013). Green discusses in his TED presentation (2013) the production of a 20-story building (figure 1).

Figure 1: Green's wooden skyscraper proposal render.

When this fictional building would be build out of concrete it would emission an amount of 1200 tons of carbon dioxide. This emissions are produced due to the transportation and the manufacturing of the concrete. When building this 20-stories building out of wood, the wood sequester about 3100 tons of carbon dioxide. So the building would work as a carbon dioxide storage. The difference between the two variants is 4300 tons carbon dioxide, which is equal to 900 cars removed from the road in one year (Green, 2014). Skidmore, Owings and Merrell (SOM) claims in their research (figure 2) that building a skyscraper of 30 stories in (partly) wood can cut the carbon dioxide emission by 70% (SOM, 2013).

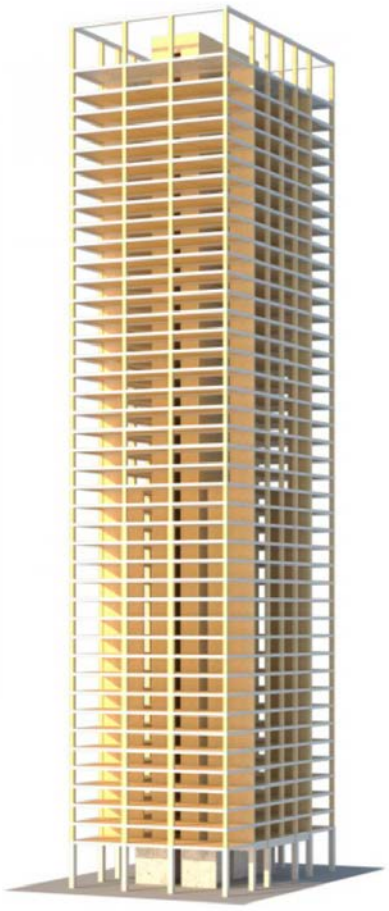


Figure 2: SOM's wooden skyscraper proposal render.

With conventional wood techniques it would not be possible to build to such great heights in wood (Green, 2013). With a relatively new technique, Massive Timber panels, also named Cross Laminated Timber (CLT), it will be possible (Green et al, 2013). The great thing about building with wood is that it renews itself. Spruces, used to make the large CLT are considered as fast growing trees. Rob Lambe, the managing director of Willmott Dixon Re-Thinking, said*: "For community buildings, CLT's attributes are that it can be used to span great distances with structural integrity, it's hard-wearing, looks good and it doesn't require additional finishing. All this keeps costs down and improves resource efficiency"* Mass timber structures also contributes to the internal climate of a building (Hameury, 2006). (Miller, 2012). Furthermore CLT has proved to be very useful when it comes to seismic actions, ductile connections are critical in this case (Fragiacomo, 2011).

CROSS LAMINATED TIMBER

Cross Laminated Timber is being developed since the 1990's, first in Austria, later in Germany, Switzerland and Italy as a product which could address the amount of waste wood which was being produced by mills (Stauder, 2013). Recently CLT crossed over the Atlantic Ocean towards Canada. The United States do not even have a commercial CLT producer (Boston, 2014). CLT has proven to be a very good alternative compared to concrete in the residence building industry based on CO_2 emissions (Mohammed, 2012). Due to the cross gluing technique it becomes possible to gain mechanical properties which can compete concrete elements (Mohammed, 2012) (figure 3 and 4). CLT does not shrink during its lifespan, it is also easy to produce complete walls, floors and roof out of it.

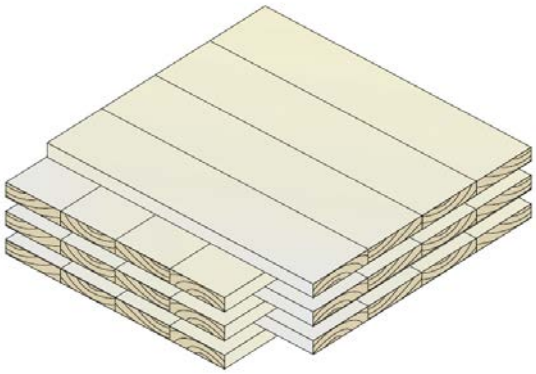


Figure 3: CLT layout with longitudinal and transverse planks.

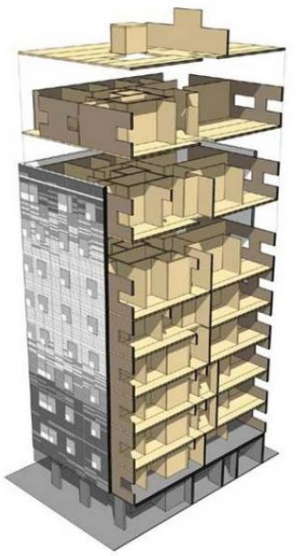
Figure 4: Typical Cross Laminated Timber panel.

No structural lintels are required, openings are performed by cutting holes into a CLT plate. The behavior of CLT panels outdoor is comparable to sawn lumber of the same species, CLT is not intended to be exposed to the outdoors and the panels should be protected from rain and high relative humidity levels with a properly designed building envelope. Like conventional wood construction types, the use of basic design elements such as cantilevers and the integration of drained and ventilated rain screen walls will effectively prevent rain penetration into building assemblies. In addition, appropriate design and application of insulation materials, air and vapor control strategies, as well as ground moisture control measures are needed. Such measures will ensure that the panels will be kept warm and dry, help prevent moisture from being trapped and accumulated within the panels during the service life, and ensure the energy efficiency of CLT building enclosures according to the CLT handbook.

The building industry should consider massive timber panels as a construction material when building up to 30 stories (Green, 2012). Green compares the invention of CLT with Lego blocks, the ordinary Lego block contains 4x2 dots. Green explains that CLT plates are the 24x2 dots Lego blocks, which makes larger spans possible (Green, 2014). These panels are also very suitable for making a building stability core, the stiffness of each plate makes CLT suitable to withstand shear forces.

Besides the expanded knowledge on individual CLT panels less is known about applying them as a structure in high-rise buildings.

Only a few middle-rise buildings are made out of CLT wood. A famous example is the Murray Grove project by Waugh Thistleton architects in London (figure 5). This was one of first residential building made complete out of CLT (Waugh, 2009). The connections in this building are elaborated as can be seen in figure 6. The CLT panels where prefabricated and simply stacked upon each other on-site.



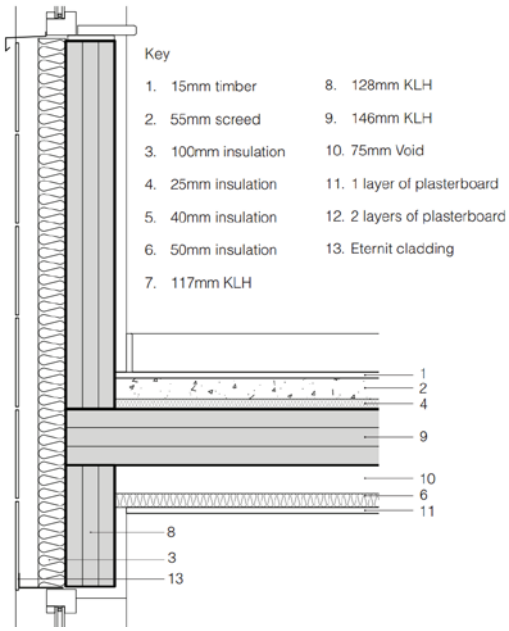


Figure 5 (upper): Murray Grove structural sketch
Figure 6 (lower): Typical façade-floor connection in CLT, Murray Grove project.

The fact that there are so little examples of CLT built buildings leads to questions about the durability of the material. Also the fire resistance has not been tested on a building as a whole. Test have been done regarding fire safety on single CLT panels (SOM, 2013) but research on building level have not been executed. The North American building codes do not allow you to build higher than 4 stories when your main construction material is wood. This has to do with historic disasters such as the great San Francisco fires at the beginning of the 20th century (Green, 2013). The regulations are concentrating on conventional use of wood while the knowledge about the use of wood has increased over the last decades. The CLT panels have a predictable burning pattern. Green and SOM both agree that a wooden structures is safer than a steel structure. When fire occurs in a wooden building it takes a long time before the structure catches fire. When a timber element is on fire it creates a "char layer" on the outside, leaving the core of the element undamaged (figure 7). When designing a building this core should be large enough to transfer the loads of the building. By over dimensioning a wooden structure it becomes possible to make the building fire resistant. A dry CLT panel contains a wood moisture content of 12%. This moisture content will evaporate during a fire and strengthen the fire protection. Another way to increase the fire safety is to develop a more fail-safe sprinkler system. Currently this is being investigated in Austria, where a wooden high-rise building still needs to pass the building regulations check (French, 2015).

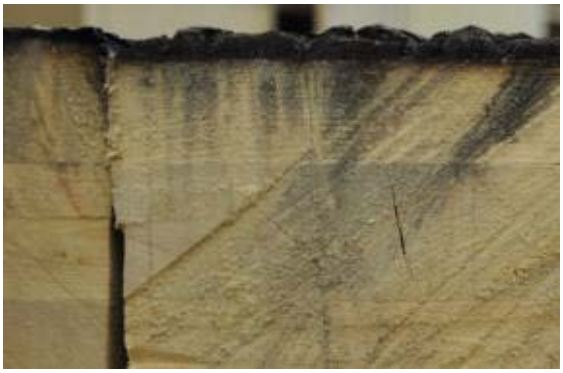


Figure 7: Burning pattern typical CLT panels.

MATERIAL EFFICIENCY

Tham & Videgård Arkitekter, Stockholm based architects proposed a wooden high-rise complex in Stockholm. *"The buildings are constructed entirely in one material, Swedish solid wood, from the frame to the facade, finishes and windows,"* says the architect (Tham, 2015). Swedish solid wood is a proven usable structural building material, but it is questionable if Swedish solid wood alone will make a durable and comfortable building. Since the design of this building ensemble is still in a preliminary phase it is hard to guess how problems will be solved in the end. By suggesting making the building completely out of wood raises the question of this building is about smart material usage, sustainability and so on or if it is about building in wood?

One of the most important factors SOM discovered during their research is the weakness of CLT connections. The massive timber plates function quite well regarding strength, stiffness and costs. The timber connections however are weak or expensive. SOM solved this by making the connections in concrete. They did not stick to the material where the research was about, but thought beyond the material to come to a simpler solution. The arguments to build high-rise structures in wood are strong, but to make buildings 'complete' out of CLT is maybe not the way to go. CLT is being compared with concrete when it comes due to the prefab way of construction and the mechanical properties of such panels. The big difference with concrete is however that we evolved the way we use concrete. It is very common to spare concrete by pre-tensioning beams or apply prefabricate hollow core slabs. A Cross Laminated Timber panel has benefits, but it is also not very efficient. The properties of wood are not perfectly used, it is not that hard to make a stiff box (sandwich panel) out of timber beams for example. The fact that CLT is easy to build with on the building site seems to hide this problem. And it is also questionable of every wall in an apartment should be a structural wall.

Cost reduction is one of the most important factors in practice when choosing a structural

material. This is one of the reasons why prefabrication is an interesting building method. Prefabrication gives the opportunity to make complex building elements in a factory under perfect circumstances. Prefabricated CLT panels are glued slices of wood glued together, nothing more and nothing less. This results in a not very intelligent building system, but in a system with a large amount of wood and glue. Pickler claims that using a lot of wood is not a problem: *"CLT is manufactured 2x6 lumber from trees harvested from sustainably managed forests, and mostly Mountain Pine Beetle kill trees. If we don't use them, they decay and emit carbon back into the atmosphere"* (Pickler, 2014). This seems valid when the amount of wooden structures does not increase extremely in the coming years. When looking at a more durable solution regarding material usage this way of thinking will not be sufficient in the future.

HYPOTHESIS

A more hybrid structural system may be the solution to build more efficient wooden structures. Where different materials are used in their strength and work together. Green is focusing on the carbon dioxide emission problem in cities worldwide. Sustainability is more than reducing CO_2. It is also about materials and natural resources. When taking that into account it would be logical to be more aware of applying materials in a smart way to save the amount of materials needed to build a high-rise building. SOM recognized the critical points of a CLT structure are the connections between floors and walls (SOM 2013). Therefore SOM decided to execute the connection in concrete to make the design more economical. SOM decided when CLT or timber are not a suitable material, just use another material which does the job better.

The goal of the wooden high-rise buildings should be differently formulated. Instead of: how can we build high-rise wooden buildings? The question should be: Which role can wood play to make a sustainable high-rise building. By formulating the question in this way it opens the possibility to think in wood, but when needed also allows you to think beyond wood.

RESEARCH QUESTIONS

The problem stated before can be elaborated in the following research and sub questions:

In what way can a 30 stories tall timber building be designed in a more material-efficient way than the Cross Laminated Timber structures proposed by Green and SOM?

- What are the main advantages of Cross Laminated Timber panels and what are the main drawbacks?

- Are there any alternative timber products which can make average spans, comparable with CLT and be more material efficient as CLT panels?

- Is it possible to combine several materials into one system without making it logistically complicated – and therefore less sustainable?

POSSIBLE RESEARCH APPROACH

The approach of the research should be similar to other researches about high-rise wooden buildings. When it comes to wooden high-rise structures there are only a few elaborated studies. The studies of Green and SOM have both the same character, both consider a case-study of a fictional design of a tall wooden building. Both including rough floorplans, façade proposals, global calculations, basic details and experiments regarding fire safety. Both studies claim that a timber building with more than 30 floors is reachable. By using a case-study of a fictional design it will be easy to compare the research with the research done by Green and SOM. In this way it becomes clear if a hybrid construction or using wood in a more efficient way will be beneficial compared to a skyscraper completely out of CLT. Beneficial is in this case multi interpretable. Important things to compare with the other researches are the amount of materials used, not only wood but also concrete and steel, the amount of prefabrication that is needed and the global costs of the building.

The global steps for further research, step two has different options, which option gives the most beneficial design is not clear since a lack of research so far:

1. Evaluate the researches done by Green and SOM, the amount of wood applied, the amount of CO_2 the building produces, the building costs, durability, fire protection and other critical points in the design.
2. Design a competitive high-rise structure with the benefits of CLT kept in mind, but also from the material efficiency point of view.

2.1 Use SOM's or Green's proposal and change the CLT floor plates to concrete-wood combination floors.

2.2 Use SOM's or Green's proposal and change the CLT floor plates to hollow-core wooden plates.

2.3 Discuss whether structural walls are needed, change them into less bearing timber frame wall when possible.

2.4 Option: Design another system with a megastructure out of concrete with CLT walls and floors as an infill.

3. Evaluate the design, make preliminary structural calculations, and calculate the expected CO_2 emissions and the amount of materials used.
4. Evaluate the comfort advantages and drawbacks. What happens with the dynamic behavior of the building? The thermal mass and the acoustic qualities behavior of the building.
5. Compare the design with the wooden high-rise structures proposed by SOM and Green.
6. Conclude which design will be more sustainable and in what way.

EXPECTED RESULTS

Since the research still needs to be executed the expectation of the results is comparable to the hypotheses. It is expected that the proposed building design acts less well as a CO_2 storage, since there probably will be used less wood.

Figure 8: Lignatur Hollow core timber panels.

Another drawback that could be expected is the lesser heat storage capacity of the floors and walls when using lighter materials, but it is not clear if this really is the case. When using timber alternatives such as hollow core plates (Lignatur) there are great opportunities to spare material and to make floors more efficient. These plates allow architects to integrate acoustic measures and installations into the floor.

Other results that might be expected are based on recently (being) built high-rise timber buildings. These buildings use a different building system than stacking CLT panels, nevertheless wood takes a central place in the structural design of these buildings.

Patch22 by Frantzen et al architects in Amsterdam is a building made out of wood and concrete, it is currently (2015) under construction. The floors in this new middle-rise building are built-up by a timber frame with a concrete pressure layer on top. This is a very common way of restoring old buildings, but can according to Frantzen, also be very beneficial for new buildings. Wood can be used for the tension zone while the concrete layer forms the compression layer and provides the fire protection and acoustic qualities. Together they form a floor which can span large distances (figure 9) (Frantzen).

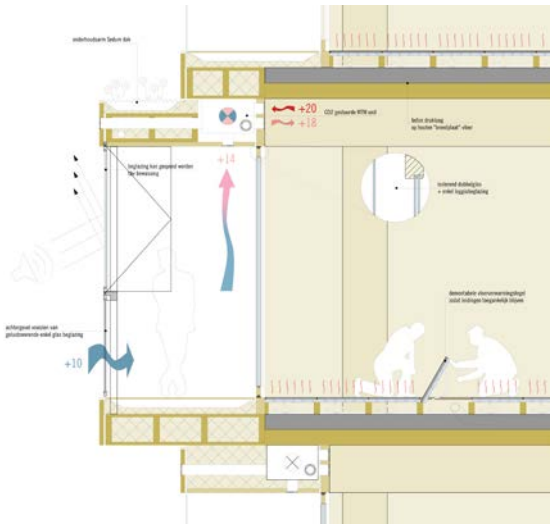


Figure 9: Patch22 section with concrete-wood floor.

Another example is the Treet building in Bergen, Norway. This building designed by Artec Prosjekt Team AS, holds the world record for 'tallest wooden building' with 15 floors. This building however is not build with CLT as a main structural material, but with conventional glue laminated timber (glulam). The architects have designed three tables stacked upon each other out of glulam, these tables have a concrete tabletop to increase the weight of the building and therefore improve the dynamic behavior of the building (figure 10).

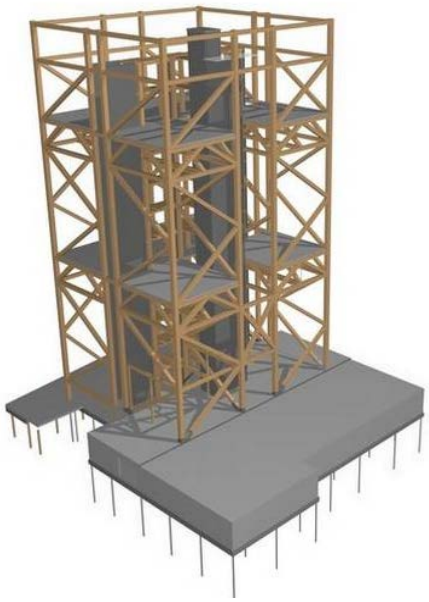


Figure 10: Structural drawing with three tables, Treet building, Bergen

These concrete platforms act also as a solid floor where prefabricated CLT modules are placed upon, the modules are stacked up to four stories height. The elevator shafts are also executed in CLT, since the CLT panels are really well performing regarding shear forces. To limit the need for maintenance a permanent weather protection system was chosen. The north and south facades are executed in glass to protect the glulam structure. The east and south façade are cladded with metal sheets to protect the glulam.

Van de Kuilen et al, also suggest a separation between a 'megastructure' and a substructure. In his case the megastructure is not made out of a glulam frame but out of concrete of steel (figure 11).The megastructure is filled in with CLT walls and floors. In this case, the main structure of the building may not be recognized as a timber structure, but the CLT plays a decent role to cut down CO_2 emissions (van de Kuilen et al, 2011).

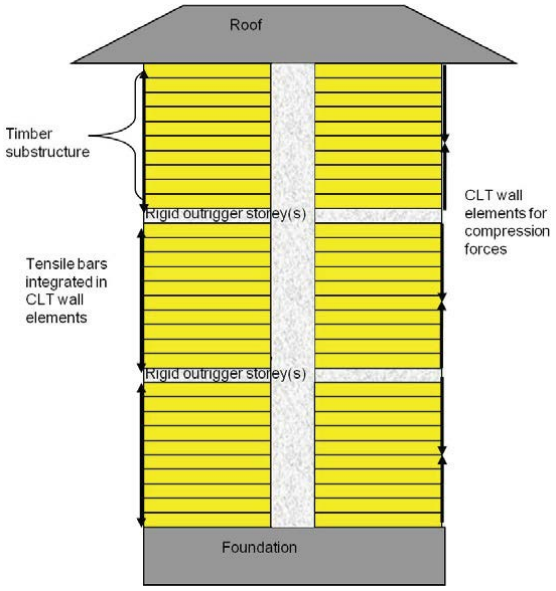


Figure 11: CLT with enforced megastructure, Van de Kuilen

EXPECTED CONCLUSION

The expected conclusion could be that a hybrid structure will be more beneficial regarding sustainability. Although the CO_2 emission

benefits regarding mass timber structures are substantial, it should be considered to design more material-efficient, so less trees need to be cut and less glue needs to be used. A very important note is that a lot of unknown things about high-rise timber buildings executed in CLT still exist. There is not a physical model to do tests with, there are no static non-linear and dynamic non-linear at time history analysis available. Also the wind vibration analyses are not available yet. When this research is done it could make CLT more or less attractive as a main building material for high-rise buildings.

Summarized can be said that the development of high-rise timber buildings creates new opportunities for making high-rise building more sustainable. Research done so far sometimes creates the feeling if building in wood has become the goal on its own, instead of building more sustainable skyscrapers. The way the proposed research will be elaborated can vary, since there are several options to review the wooden skyscraper concept. Please note that the research proposal in this paper is very rough, this paper is trying to create the awareness of alternative research. A fresh look at high-rise timber structures, in combination with other materials or other building methods can make it more material efficient and therefore more economically and/or sustainable. In this way we can really make new steps when it comes towards sustainable high-rise structures.

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