A project contribution to the development of sustainable multi-storey timber buildings

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ABSTRACT: Wood is a natural material, renewable, easily recyclable, and able to store carbon-dioxide, which makes tall timber buildings a solution with potential to answer the main sustainability targets. Cross laminated timber (CLT) has been pointed out as the best wood-based material to make this ambition a real thing. In order to understand why, this paper introduces the material and describe some demonstration buildings recently built.
Based on diagnosed weaknesses of CLT buildings, it is presented an initial propose for a new CLT/glulam hybrid construction system, called Urban Timber (UT) system, which aims be able to support taller timber buildings. The main motivation was the development of a wood-based structural solution that provides more spatial flexibility and wider versatility for visual architectural expressions. The system is described and illustrated, considering concerns related with structural behavior, architectural value, structural connections and wood shrinkage.

1 TALL TIMBER BUILDINGS IN THE CITY

1.1 *A brief introduction*

The continuous increase of the urban density all around the world forced cities to grow taller, making tall buildings an ordinary typology in developed cities. The urban population keeps growing, foreseeing that until 2050 the world population living in cities will reach 70% (Green & Eric Karsh 2012), which indicates that tall buildings will become even more common. Unfortunately, tall buildings are generally linked to great negative impacts on environment, raising the need to look for new environment friendly solutions. Tall timber buildings are a concept that emerged connected with this need, betting on wood sustainable profile as the key factor to reduce the negative environmental impact of construction sector. In some countries where timber has a social character, such as Sweden, German and Japan, timber is positively appreciated as a building material (Stehn & Bergström 2002). However, this subject can face serious barriers in countries where wood culture doesn't exist. Regardless of these difficulties, tall timber buildings are an exciting and current topic, expecting that their qualitative advantages overcome remaining socio-cultural barriers.

Cross laminated timber (CLT) is an engineered timber product that has been largely associated to the concepts of tall timber buildings due to its enhanced mechanical properties, mass and technological facilities. CLT constructions are often cited as a great sustainable solution due to their capacity for store a large amount of carbon dioxide (Green & Eric Karsh 2012, Omland & Tonning 2009).

1.2 *Sustainability targets – Social, Environmental, and Financial*

Regarding to sustainability concerns, CLT tall timber buildings has been proofing their viability in all three main sustainability targets, namely: environmental sustainability, financial sustainability and social sustainability (see Fig. 1). Sustainable profile linked to timber as a construction material can be a strong ally to recent European environmental policies, namely EU's 20/20/20 plan. Indeed, timber is a natural material, renewable, recyclable and able to store carbon dioxide. This last feature is the most important one once each timber building works like a carbon dioxide reservoir, which will only be emitted into the atmosphere upon combustion or decay of timber. Some numbers related with carbon storage of CLT buildings has been recently published. According to respective designers, Stadhaus, in London, saved 310 tonnes of carbon (Kucharek 2009) and Forté, in Australia, promoted an overall saving of 1451 tonnes of Carbon (Heaton 2013).

The financial sustainability of CLT is closely related with savings provided by technical facilities and rigorous project design. In one hand, material production is industrialized and based on a computerized numerical control (CNC), which ensures a high precision of elements demanded and reduces waste material. On the other hand, the simplicity of construction, associated to timber easy handling and prefabrication allows a significant reduction of construction time, to simplify the site apparatus and an increase of the on-site safety. As consequence of these advantages, promoters of Stadhaus and Forté experienced a fast construction time, 11 and 12 months, respectively, with a reduced site team and less and low-tech equipments (Silva et al. 2012). This reduction represents approximately a saving of 30% on construction time when compared to a concrete system (Patterson 2013). However, based on numbers pointed by economical analysis, CLT is still 5% more expensive than a similar solution in concrete. This fact is related essentially with the large amount of timber used and with the use of gypsum boards to fulfill fire safety performance (Winter et al. 2012).

Finally, social sustainability is related with mental and wellbeing of people, a dimension where quantitative and qualitative aspects should be carefully balanced. In other words, a dimension where architecture should be pragmatic, answering issues like daylight, economy and energy consumption, as well as abstract answering issues related with architectural expression and spatial organization and orientation. As regards to functional and safety requirements, there are research initiatives that have assessed the safety of a CLT tall building in several areas, such as: fire safety (Dagenais et al. 2013, Frangi et al. 2008), durability (McClung 2013, Patterson 2013), sound insulation (Hu & Adams 2013) and thermal performance (Glass et al. 2013).

The design versatility is a chacteristic of CLT construction system however, when applied to tall buildings, the common systems exhibit some spatial limitations related with great number of structural partition walls, as well as limitations related with opening dimensions. For that, the present paper is essentially focused on exploiting a new way to overcome these limitations.

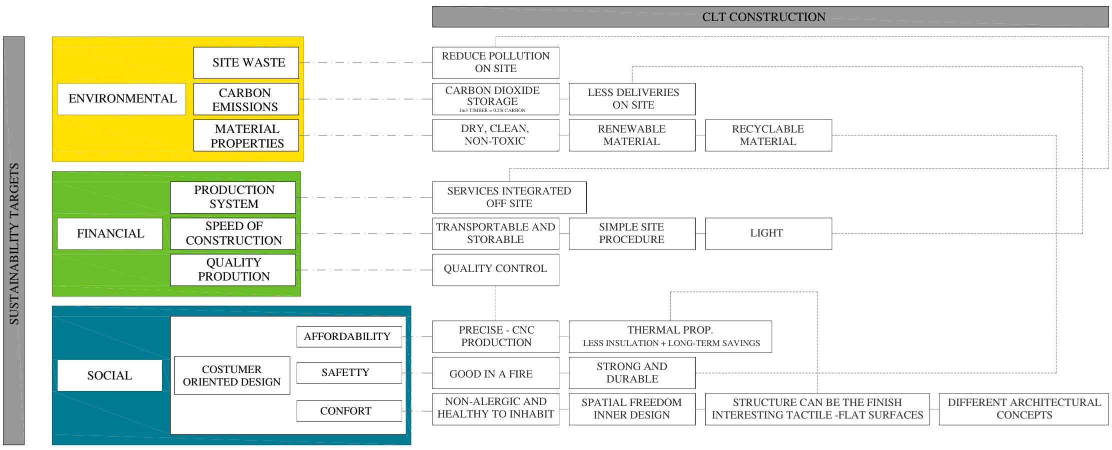


Figure 1. Sketch about correlation between sustainability targets and CLT construction.

2 CLT AS A BUILDING MATERIAL

2.1 *The plate*

CLT is a prefabricated solid engineered wood product composed of switched orthogonally bonded layers of solid-sawn timber or structural composite lumber. As final result CLT exhibits a panel shape, different from well known linear timber elements. Besides, cross layers provides to CLT panels higher strength and stiffness properties in their both directions, being able to take up forces in-plane as well as perpendicular to the plane. Thus, CLT panels may work as a shear wall as well as a slab (Bejder 2012).

CLT elements introduce timber in the field of surface-based expression, known in society since 1970's when emerged prefabricated buildings in concrete (Falk 2005). But, better than concrete, CLT offers huge format, light weight and easier workability. The dimensions of panels can be adjusted according to project needs, however there are dimensional limits essentially related with transport. Panels can have from three up to seven layers, which means thicknesses between 42 and 500mm. Width and length of panels can go up to 4800 and 30,000 mm, respectively. But, due to transportation and assembling restrictions width and length of CLT panels are limited to 3000 and 16,500mm, respectively (Augustin 2008).

The adaptation of CLT to engineering and architecture practices has been described by some authors. Falk (2005) defined structural behavior of structures based on timber *plates*, explaining the significance of orientation of walls and shear-walls as well as warning for stability dependency on both orientation and jointing. Regards to architectural issues, Bejder (2012) defined different possibilities to construct with CLT. According to that work, there are three different ways to build with a *plate-based* system, which result in distinct final architectural expressions and spatial configurations (see Fig. 2).

(a) (b) (c)

Figure 2. Three different spatial configurations based on plate properties suggested by (Bejder 2012). (a) *Enclosed box*, (b) *dissolved box* and (c) *'floating' structure*.

2.2 *Limitations imposed by building scale*

Regarding buildings with a reduced number of floors, CLT is a very attractive material possessing a significant number of qualities. The massive and isotropic *plate* allows for great freedom during designing process, allowing different building overall shapes, different spatial configurations, and freedom on openings location, shapes and size. Further, force transferring properties of a plate structure allows floor-structures with wide spans (approximately 7.5m (Augustin 2008)), wall-structures working as deep beams, and columns can be used as supports without main beams (Falk 2005).

However, when CLT is the only structural material of a tall building, the design freedom suggested before is limited. Structurally, CLT has been mentioned as a good material to build tall with timber once it is a massive material with improved mechanical properties. Further, massive construction is characterized by its monolithic behavior, based on distribution of bearing walls able to provide to structure a higher level of strength and stiffness.

Nevertheless, tall building requires the adequate stiffness to answer horizontal forces derived from wind or hazards, which means the need of increase the mass of structure. Thus, CLT construction took refuge in a super massive system called *cellular construction*. It can be classified as a 'selfish system' grounded on the multi-functionality of CLT claiming that the entire building should be built up with CLT elements. In other words, it is a system in which CLT should shapes all structural elements.

Cellular construction has been recently applied in some recent tall buildings exposing some important limitations associated to this system. Beyond the stiffness requirements, this kind of system can promote progressive collapse requiring extra load paths through the increase in the number of structural walls. At the end, the building shows an enclosed external image with small openings and inner spaces, excessively compartmentalized. This last is the reason why typical CLT tall buildings have been essentially limited to residential buildings.

Aware of that obstacle, enthusiasts of tall timber construction have started to encourage engineers and architects to work on new solutions able to offer greater freedom to designers and meet actual customer needs. There are already some proposals to reduce the excessive partition space, such as: located reinforced cores and some hybrid structural systems that promise to boost the emergence of new ideas. New solutions should bet on exploration of material strength, local strengthening of bearing points and increase stiffness, in order to allow more daring and creative results (Wells 2011).

3 DEMONSTRATION CLT BUILDINGS AND THEIR CONSTRUCTION SYSTEMS

3.1 *Cellular construction*

In last few years some CLT tall buildings, with a range of storeys between 8 and 10, have been built in order to prove their viability and their advantages. The most known examples are Stadthaus and Bridport in London (UK) and Forté in Melbourne's Docklands (Australia). All buildings are based on *cellular construction*, in which CLT shapes walls and floors. Structural stability is provided by bearing walls and stairs/shift cores, built with thicker CLT elements or a double layer wall.

Despite the excessive number of partition walls present in these three buildings, it is possible to note some flexibility on location and orientation of bearing walls and cores. All three buildings present different overall shapes. Stadhaus presents a simple square implantation, Bridport bets in a less slender long shape, while Forté suggests something more irregular, broking the square monotony with protrusions and angles which also offer greater diversity of views to different apartments. However, all of them show an external expression of an enclosed box (Silva et al. 2012). This is a consequent result when a construction system is entirely based on CLT elements, which requires the location of vertical load paths in façade elements.

Regarding to functional requirements, like fire safety, thermal and acoustic behavior and durability, all studied buildings respected the building code requirements. In fact, nowadays the ability of CLT to answer these functional requirements is not an assumption anymore. As mentioned in point 1.2, several research projects have been studying the best construction measures to ensure that CLT buildings can offer safe and comfortable solutions. Usually, to respect fire and acoustic requirements the walls sections are covered with 1 or 2 layers of gypsum boards, creating an air gap where is located the acoustic insulation material. Thermal behavior is not a matter of concern once low heat conductivity of timber answers the requirements itself. At last, durability is guaranteed through the application of impermeable and breathable sheets on exterior face of CLT elements, protecting timber from water contact and significant changes in its moisture content.

3.2 *Proposed innovative solutions*

Challenging the limitations of CLT tall buildings, some innovative proposals, based on hybrid and lighter concepts, have been emerging. Barents house, project by Reiulf Ramstad Architects (Reid 2010), and FFTT system (find the forests through the trees), developed by Michael Green and Eric Karsh (Green & Eric Karsh 2012), are two of these proposals looking for solutions able to offer greater spatial amplitude, suitable to non-residential uses and reach higher heights.

Barents house is a project for a timber building with 20 storeys which bet in a structural system that combines CLT floors, glulam beams, columns and diagonals, and a concrete core. FFTT system is able to reach 30 storeys and bets on the combination of CLT walls and floors with steel beams. The reduction of timber amount, and consequent reduction of space partition, is possible due to the increase in the building stiffness warranted by concrete and steel elements (Silva et al. 2012).

4 UT SYSTEM

Urban Timber (UT) system is an initial proposal, similar to the hybrid solutions presented above, looking for a tall timber solution able to answer actual demands from society while respecting the principals of sustainability. *UT system* can be classified as a hybrid timber solution once it tries to propose an entirely timber-based system, avoiding the use of steel or concrete, but denying the selfish '*all with CLT*' concept. It combines two different timber engineered products, namely CLT and glulam, resulting in a lighter solution able to conceive more economical and challenging buildings.

4.1 *Structural system*

Structurally, *UT system* is inspired in the *bundled tube* concept, which works like a cluster of individual tubes connected together in such a way that they behave as a single unit. The advantage of such kind of concept is that the three-dimensional response of the structure result in an improvement of strength and stiffness provided by cross frames in the building (Ali & Moon 2007).

The proposed system is based in the combination of CLT and glulam, in which CLT shapes floors, walls and deep beams, while glulam shapes only beams. CLT walls have the function to resist gravity loads, either with a vertical load path or an oblique one, and resist lateral loads by means of shear walls. CLT floors work together with glulam beams distributing loads to CLT walls, improving the building stiffness and avoiding the effect of progressive collapse. Finally, CLT deep beams sew up all individual tubes in the building perimeter.

Tall buildings have greater vulnerability to lateral forces, especially wind loads, which means that the building perimeter has more structural significance. So, *UT system* suggests a structure in which major part of lateral load-resisting system is located on building perimeter, but as recommended for any exterior structural system, there are also some minor components within the interior of the building (Ali & Moon 2007). Further, considering the fact that shear-plates provide more stiffness than the corresponding elements in a frame construction (Falk 2005), the external lateral load-resisting system is performed by CLT shear walls positioned in building perimeter and oriented perpendicularly to facade plane.

Figures 3 and 4 exhibits a proposal for a building based on *UT system* principals in which both external and internal lateral resisting elements are arranged in two principal orthogonal directions. As shown in Figure 3, lateral load resisting system can be improved by means of great shear walls, located in building corners oriented in both main axis of structural system.

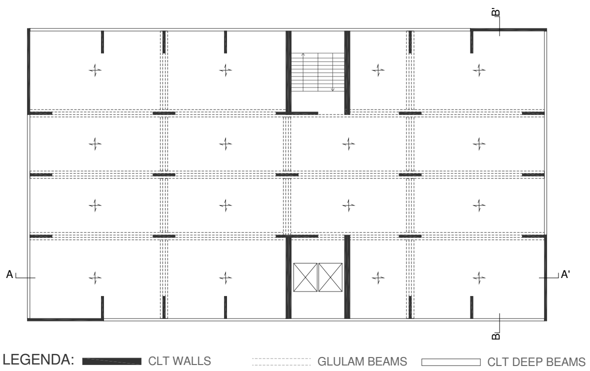


Figure 3. Structural plan proposal of *UT system*.

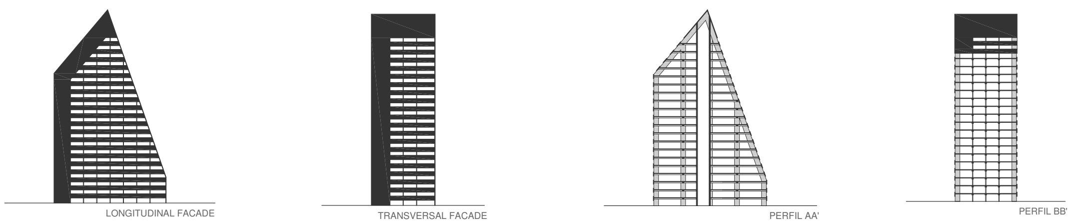


Figure 4. Facades and cross sections of a proposed building using *UT system* .

4.2 *Wood moisture content concerns*

Shrinkage considerations should always be considered during the design process of a tall timber building, even using timber engineering products subjected to a rigorous control of moisture levels (between 10 and 14% (Augustin 2008)).

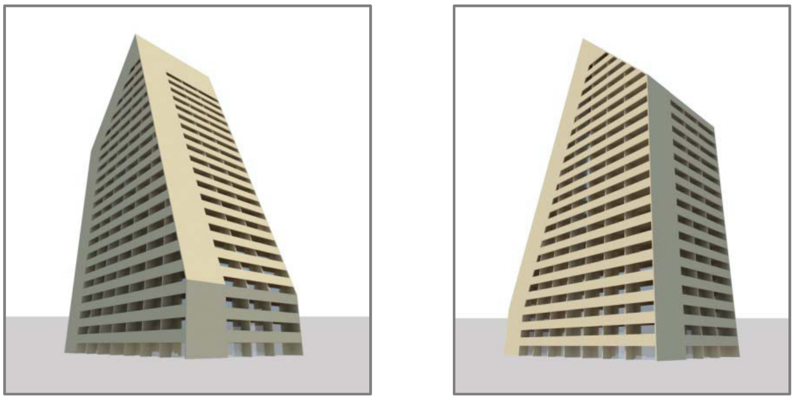
Based on cross lamination benefits, it is proclaimed that CLT is a dimensionally stable material along its main axis (Augustin 2008). However, as a precaution, *UT system* is based on balloom-frame construction, taking advantage of panel length to experience slightly less accumulative shrinkage over the height of the building. A more troubling issue is related with shrinkage across the thickness of CLT that is logically greater due to its solid timber composition. To overcome this matter, *UT system* presents the combination between CLT floors and glulam beams as a possible solution once in this way CLT floors don't rest directly in CLT walls. In this way, glulam beam ensures a continuous support to CLT floor which is not only dependent on steel connection between panels, reducing any influence that moisture variations could exert on connections behavior.

Another important issue concerning moisture is the exposition of CLT facade panels to two distinct environments (exterior and interior), which can cause some distortions on those structural elements (Lepage 2012, McClung 2013). In *UT system*, the placement of structural walls perpendicular to façade can reduce the significance of this subject when it consider the position of balconies in the entire perimeter of building. In this way, the contact of the structural elements that are part of façade system with the interior environment is limited.

4.3 *Architectural considerations – Architecture being pragmatic as well as abstract*

The main architectural focus of *UT system* is to maximize the freedom in the creative act that architecture represents. A powerful vocabulary for a variety of existing building forms it is proposed.

Beginning with building plan shape, in a bundled tube system, the individual tubes could be of different shapes, such as rectangular, triangular or hexagonal (Ali & Moon 2007). This plan diversity is also possible with *cellular construction* as proved by demonstration buildings described in point 3.1. However, in buildings supported entirely by CLT elements the irregularity of building shape only results from a simple extrusion of plan shape. So, as shown in Figure 5, the great innovative proposal of *UT system* is the possibility of a volumetric freedom, allowing angles between ground and façade planes.



(a) (b)

Figure 5. 3D model of a proposed building based on *UT system*.

Keeping the discussion on external view, the orientation of CLT walls perpendicular to façade allows wider openings, and CLT deep beams allows a strong sense of horizontality not possible with a typical *cellular construction*. Further, façade walls can perform a significant role on solar protection and can also be designed to create different façade effects. That's when the technology behind CLT production can be useful to architectural expression. The CNC technology associated to CLT production enables the production of panels with different shapes without prejudice to the production process. Despite prefabrication is often correlated with modular architecture, this don't means that it don't allow personalized solutions (Larsson et al. 2012).

Relatively to internal spaces, *UT system* don't offers an extreme open space concept, as proposed by Michael Green with FFTT system, however, it allows to place interior frame lines without seriously compromising interior space planning. Moreover, with a *bundled tube* concept it is possible to free vertical cores.

UT system is the result of a process that tries to dissolve the box suggested by *cellular construction*. As result, the perception of the plates as a bearing skeleton increases and the spatial enclosure is generated by a composition of separate elements. Considering the spatial configurations proposed by (Bejder 2012), *UT system* is located between the called *dissolved box* and the *'floating' structure*. Vertical elements do not define the interior space while CLT deep beams define the relation between interior and exterior.

4.4 *Joints*

Joints in timber play a significant role on behavior and capacity of the structure, namely on building stiffness and energy dissipation (Fragiacomo et al. 2011). Timber connections exist in a great variety due to timber workability, but they have to be adequately selected and designed depending on each situation.

CLT connections are usually based on simple and relatively low-tech principles, mainly based on self-tapping screws. Exploiting these advantages, *UT system* suggests connections based on self-tapping screws and steel rods.

The main connection in *UT system* includes CLT and glulam elements, in which glulam beams perform an intermediate role transferring loads from CLT floor to CLT walls. As CLT floor rests on the top of glulam beam, the connection between them is based in the simple insertion of self-tapping screws perpendicular to the grain axis. Differently, the connection between glulam and CLT walls is performed by steel rods which connect two glulam beams and a CLT wall located between them. Steel rods were preferred instead of self-tapping screws in order to ensure that the two glulam beams work together and, therefore, an improvement in the connection stiffness is obtained (see Fig. 6).

The connection of CLT walls and floors with CLT deep beams is performed by simple self tapping screws inserted diagonally to CLT planes (see Fig. 6). Screws are arranged under an angle of 45°, (or less when CLT deep beams are sloping) between screw axis and member axis in order to provide a higher load-carrying capacity compared to common shear connections due to the high withdrawal capacity of the self-tapping screws (Krenn & Schickhofer 2009). The use of steel plates is avoided once the connection can be located in elements exposed to external environments.

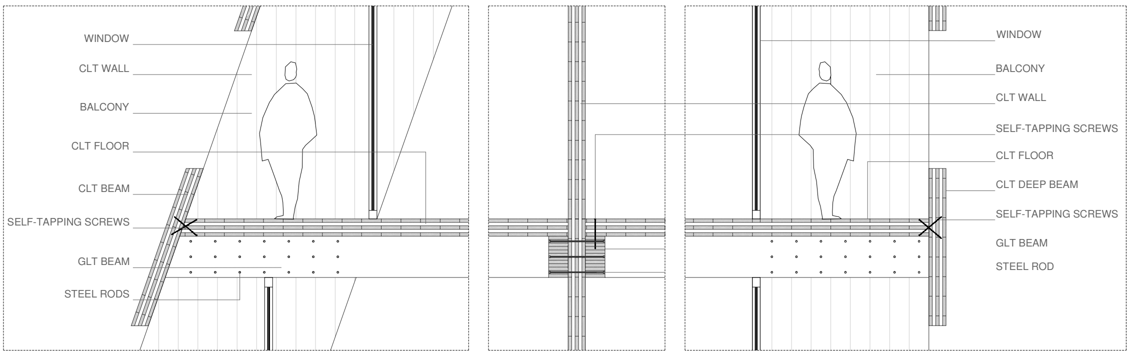


Figure 6. Details of *UT system* connections.

5 CONCLUSION

Obviously, the future of CLT in urban context should not be only based on tall buildings. However, this kind of buildings has been proofing potential to be a well spread typology in denser cities. Actually, tall CLT buildings have been mainly supported by qualitative reasons, such as sustainable advantages, but this typology can't develop properly only based on that. So, CLT systems must look for more economical solutions able to support taller buildings and more challenging architectural solutions.

UT system tries to make the CLT use more attractive to construction market looking for a solution able to answer adequately quantitative and qualitative the actual requests. The focus on a timber hybrid solution allows both, keeping the ecological advantages and reaching a higher level of versatility and freedom in the architectural design. This system is still in an initial phase of development being necessary to assess its real viability with further research steps, namely to study the design taking into account the structural and functional requirements of the existing building codes.

Finally, it must be said that the search for new CLT constructions systems should keep exploiting properly the multifunctional qualities of CLT plate-shape, generating new ways of thinking, designing and building with wood.

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