UT SYSTEM: A STRUCTURAL SYSTEM TO BUILD TALLER URBAN TIMBER HOUSES WITH THE ASPIRED SPATIAL FLEXIBILITY

Catarina Silva, Jorge M. Branco* and Paulo B. Lourenço

1: ISISE, Department of civil engineering
School of Engineering
University of Minho
4800-058, Guimarães

e-mail: Catarina.vilaca.silva@gmail.com, jbranco@civil.uminho.pt, pbl@civil.uminho.pt

Keywords: timber urban housing, UT system, tall timber construction systems, cross laminated timber, space flexibility.

Abstract In past few years, in consequence to the continuous increase of urban densities and seeking for a more sustainable profile for construction, some new proposals for tall timber city housing have emerged. The development of new wood-based materials, like cross laminated timber (CLT), has made possible to believe to build high with timber. Demonstration buildings located in different locations around the world contribute to the development of this new concept of urban housing. With the exception of few recent proposals based on hybrid systems, majority of buildings so far built are fully based in the monolithic construction system offered by CLT panels. Despite all the advantages related with this monolithic system, two main important weaknesses related with architectural freedom have been pointed out: the excessive compartmentalization of inner spaces and the external expression of an extruded box with reduced openings.

Inspired on new CLT/steel and CLT/concrete hybrid proposals and their advantages in comparison to the CLT monolithic system, a CLT/glulam hybrid construction system, named UT system (urban timber system), has been developed. CLT remains the main structural material in the UT system but, glulam linear elements are used to reduce the CLT walls both inside and in the building perimeter. Further, based in the bundled tube concept, UT system looks into the possibility of overcome eccentricity problems caused by non-symmetrical location of vertical cores and consequently, offers more design freedom.

UT system is described and illustrated, considering concerns related with structural system, tall building specificities, construction sequences, architectural design possibilities, moisture effects, durability, fire resistance, acoustic performance and joints between timber elements.
1. INTRODUCTION

1.1. Why is better to live in denser city centers?

Despite people concerns about living in urban apartments, forecasts suggest that until 2050 the world population living in cities will reach 70% [1]. Main limitations of urban apartments are essentially related with reduced areas, lack of outdoor space and reduced privacy due to neighbors’ proximity (especially above and below). However, there are stronger reasons explaining why population keeps moving to city centers: proximity to public transport, mixed-use spaces, shopping and work places, more time devoted to family, less time wasted driving home and more opportunities for social interaction [2].

This phenomenon is positive not only for people quality of life but, also to reduce environmental degradation and global warming, through reduction of car dependency, land consumption and carbon emission by households [3],[4]. However, to ensure this green city profile, it is necessary to stop the unsustainable tendency which segregates cities by zones with different uses. New urban development should be grounded on mixed-use principles, which suggests single buildings or compact urban areas where residential, retail, office, and other uses are combined. This kind of urban development can provide sustainable improvements: in social terms it can provide social interaction and increase the sense of neighborhood; in economic terms it increases the employment/population ratio; in environmental terms it encourages cycling and walking and use public infrastructures more efficiently [4],[5].

1.2. The role of tall timber in cities of the future and its sustainable profile.

The described advantages associated to denser cities raises the awareness that tall buildings are the best typology for this kind of environments. But, as tall buildings are generally linked to great negative environmental impacts, the search for new environment friendly solutions already started. Timber construction is one between some other solutions pointed to reduce the negative environmental impact of tall buildings [6].

Tall timber buildings have been proofing their viability for environmental, economical and social sustainability [7]. In past decade, some multi-storey timber buildings were built or proposed all around the world. In all those examples, cross laminated timber (CLT) has a prominent role, not only because of its enhanced mechanical properties in comparison with timber, but also due to their energy-efficiency, climate effectiveness and capacity for store a large amount of carbon dioxide [1],[8],[9]. Indeed, CLT may even be described as ‘carbon negative’ material, once it stores more carbon than the equivalent CO2 it emits from the harvesting, processing, transport and fabrication [10]. Some numbers related with carbon storage of CLT buildings has been recently published: Stadthaus, in London, saved 310 tons of carbon [11] and Forté, in Australia, promoted an overall saving of 1451 tons of Carbon [12].

Just to underline the significance of ecological footprint of buildings, Directive 2010/31/EU on energy performance in buildings was created, forcing engineers and architects to look for
almost Net Zero energy solutions. Timber may be a precious ally to professionals to reach this goal once it helps to decrease the use of energy in buildings, either in construction phase or during their whole life-cycle, and also helps to decrease green house gas emissions, amount of waste and costs [10],[13].

Regarding economical sustainability, tall CLT buildings will focus on savings provided by pre-fabrication, technical facilities, rigorous project design, construction speed and long-term savings provided by construction quality. Increasing building’s pre-fabrication level will result in a reduced construction time without making waste. Stadthaus and Forté tall CLT buildings are proofs of fast construction, being erected in 11 and 12 months, respectively [14], corresponding to reduction around 30% of construction time when compared with concrete [15]. Economically, the only factor that is fighting the advantages of CLT buildings is the total construction price, which is still 5% more expensive than a similar solution in concrete, essentially due to large amounts of timber, steel connections and gypsum boards used [16]. However, it is important to note that long-term savings in energy consumption, operation and maintenance are today more important than costs resulted from building’s erection [3].

Finally, social sustainability is related with mental and wellbeing of people, a dimension where quantitative and qualitative aspects should be carefully balanced. Building design has to consider structural and fire safety, daylight, economy and energy consumption, as well as architectural expression, spatial organization and materials used. Further, it is important to consider that use exposed wood in our buildings offer a comfortable warm experience able to reduce stress or depression and promote people health [17].

1.3. CLT buildings examples and their structural systems

Majority of CLT tall buildings built until now are based on cellular construction in which CLT shapes all structural elements. This system needs an excessive number of partitions walls, reducing spatial flexibility, and also requires vertical load paths located in façade plane [7]. The most known examples are Stadthaus and Bridport in London (UK), Forté in Melbourne’s Docklands (Australia) and Via Cenni in Milan (Italy).

Regarding buildings with a range of floors between 5 and 10, CLT is a very attractive material possessing a significant number of qualities. It allows floor-structures with wide spans (approximately 7.5m [18]), wall-structures working as deep beams, and columns as supports without main beams [19][20]. However, when CLT is the unique structural material, the design freedom becomes limited.

In consequence, some innovative proposals based on hybrid and lighter concepts emerged. Barents house, project by Reiulf Ramstad Architects [21], FFIT system (find the forests through the trees), developed by Michael Green and Eric Karsh [1], and Berg | C.F. Møller’s wooden skyscraper [22] based on timber tower research project developed by SOM [23], are some of these proposals looking for solutions that can offer greater spatial amplitude and reach taller.

2. UT (URBAN TIMBER) SYSTEM

Similarly to systems described before, UT system is an initial proposal 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 which combines CLT and glulam elements.

2.1. Structural system

Inspired in the bundled tube concept, UT system works like a cluster of individual tubes connected together in order to make them behave as a single unit. This way cross frames result in an improvement of strength and stiffness [24].

As depicted in figure 1, UT system combines CLT and glulam structural elements, in which CLT shapes floors, walls and deep beams, while glulam shapes only beams. CLT walls are the main load-carrying elements which drive loads to the foundations, either through a vertical path or an oblique one. These vertical/oblique elements works also like shear walls, resisting lateral loads by being oriented perpendicular to the façades [24]. CLT floors work together with double 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.

Figure 1. UT system. Sketch of its structural components.

A preliminary analysis of UT system, performed with SAP2000 [25], indicates that its weakest link are the CLT walls. To reach a goal of 20 storeys, CLT walls should start in first 3 floors with a thickness of 1000mm (b eff =760mm and cross layers =4 x 60mm) which decreases as the building goes higher. However, further analysis is required concerning dimensions of structural elements.

2.2. Construction system and affordability

Digital design will be a precious ally for pre-fabricated constructions systems. The building of tomorrow must be designed and produced with digital tools. This fact is of great importance once monotonous prefabricated architecture based on mass production will evolve to an original architecture based on made-to-measure components without imply a significant increase of costs [17].

Similarly to majority of timber systems, UT system is a simple system based in large
prefabricated elements: timber panels/beams are lifted by a crane and installed using either a balloon frame or platform frame system. In particular case of UT system, balloon frame system was selected as the better option, either due to construction facilities or specificities of material and structural system itself.

Speed of construction is also considered by UT system. Besides the gains of prefabrication, this construction system also allows to erect the building in stages of 3 floors per time, once CLT walls can easily reach the required 12 meters. First CLT walls are erected and properly propped, then for each floor (one floor per time) the same assembly sequence is followed: (1) double glulam beams are fixed to CLT walls, (2) CLT floors are fixed at glulam beams and finally (3) perimeter deep beams sew all vertical elements (figure 2).

Figure 2. Illustration of different stages of a building designed considering UT system.

2.3. Wood moisture content concerns
Timber engineering products are subjected to a rigorous control of moisture levels during production and it is proclaimed that CLT is a dimensionally stable material along its main axis [18]. However, design of a tall timber building must always consider shrinkage/swelling movements. UT system is based on balloon-frame construction, taking advantage of panel length to experience less accumulative shrinkage over the height of the building. In the other hand, UT system presents the combination between CLT floors and glulam beams in such a way that CLT floors don’t rest directly in CLT walls, minimizing troubles with shrinkage/swelling effects across the thickness of panel. Glulam beam ensures a continuous support to CLT floor which is not only dependent on steel connection between panels, reducing any influence that moisture content variations could exert on the connections behavior.

2.4. Building envelop and timber durability
An important concern of typical CLT buildings is related with the exposition of facade panels to two distinct environments (exterior and interior), which can cause some distortions on structural elements. UT system places structural walls perpendicular to façade reducing the significance of this subject either when it consider the position of balconies in the entire perimeter of building (when CLT wall are entirely on outside environment) or when it consider an external continuous glass façade (when CLT wall are entirely on inside
Besides shrinkage and swelling effects, moisture can also lead to timber rot, mold and mildew, which can eventually result in structural problems for the building. In the case of building facades, an effective drainage plane on all wall surface, including a rain screen assembly or a gap between the siding and exterior sheathing, is essential to allow moisture to drain away from building elements [4]. As depicted in figure 3, UT system proposes four different possibilities for façade drainage. The first two possibilities require adequate CLT sealing and cladding, once structural elements are directly in contact with external environment. For this kind of solutions it is recommended to apply separately a water vapor barrier and a wind barrier. Water vapor barrier should be applied directly in the CLT face while wind barrier should be applied after the insulation material [26].

Last two possibilities avoid CLT sealing or cladding suggesting a continuous curtain wall or a double curtain wall. These possibilities behave better in terms of durability of building envelop, but when compared with typical CLT construction these larger openings reduce thermal and acoustics benefits. So, UT system has to be associated with use of high performance windows, able to improve energy efficiency, reduce heat gain and loss, reduce noise levels, reduce condensation, improve comfort and increase daylight and views [4].

![Figure 3. Four possible drainage planes to apply on a UT building.](image)

2.5. Fire safety

Combustibility of wood is the main reason why majority of building codes restricts the use of timber as structural material, usually limiting the number of floors allowed (from 2 to 5 storeys for non-sprinkled buildings and from 3 to 8 storeys for sprinkled buildings [27]). But, contrary to the general belief, wood can be more fire resistant than both steel and concrete: (1) Moisture content of wood delays its burning; (2) wood burns with a predicted charring rate; and (3) it creates a protective char layer which allows timber elements to be exposed for extended periods of time during a fire without sacrificing structural integrity and allowing time to evacuate the building [22]. Despite all these findings there is still who claims that it is unrealistic to suppose that fire authorities will permit the unlimited use of timber for tall
buildings worldwide in the near future [28]. The main reason for this is special fire safety
designed for tall buildings: the worst scenario predicted considers that a number of occupants
located in the upper part of the building cannot leave the building neither the fire brigade can
reach the fire compartment. In these cases it is assumed that fire cannot be extinguished and
all combustible material in fire compartment will burn.

UT system was designed thinking on the advantages of exposed timber, even if is necessary to
over design structural elements and use active fire protection devices installed for detection,
alarm and suppression of fire. However, if necessary, UT system can also use passive fire
protection systems which confine fire and smoke to designated zones and protects timber
elements with non-combustible claddings to prevent timber to burn.

Considering the known strength decrease of steel connections when exposed to high
temperatures [27], UT system looks to use embedded steel connects as much as possible. When it is not possible, encapsulation is the easiest solution.

2.6. Wall and Floor systems

Quality of floor and wall systems is a parameter of huge importance to make homes more
attractive to potential buyers, especially in cases of multi-storey timber buildings. In these
cases, vertical and horizontal barriers must ensure that disturbance from one unit to the other
are avoided [29].

Relatively to wall assemblies, UT system suggests a non-load bearing light system based on
gypsum boards with high levels of sound insulation. In contrast, CLT floor assemblies are a bit more complex. Figure 4 presents two possible solutions to use with UT system based on
suggestions presented in [30]. Solution at left proposes a CLT floor assembly with flooring
and ceiling while solution at right depicts an assembly without a ceiling. Both solutions
respect sound transmission classes (STC) and impact insulation class (IIC) as well as reduce
flanking transmissions that goes through shared structural building components [29].

Figure 4. Two possible wall/floor systems to apply on a UT building.

2.7. Connections

CLT connections are usually based on simple and relatively low-tech principles, mainly based
on self-tapping screws. UT system also 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 go through two glulam beams and a CLT wall located between them. Steel rods were preferred instead of self-tapping screws in order to make two glulam beams work together and to improve the stiffness of connection as a cohesive set (figure 5).

The connection of CLT walls and floors with CLT deep beams is performed by simple self tapping screws inserted diagonally to CLT planes (figure 5). 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.

![Figure 5. Connections details proposed for UT system.](image)

### 2.8. Architectural considerations and adaptive Design

The main architectural focus of UT system is to limit, as least as possible, the creative act of architects. For that it looks to create a powerful vocabulary for a variety of existing building shapes. UT system is the result of a process that tries to dissolve the box suggested by cellular construction.

Considering external building shape, UT system presents two great innovative proposals: (1) it allows angles between ground and façade planes, something hard to build with monolithic CLT systems; (2) it allows building sliced floors, breaking the façade continuity (figure 6). In terms of external expression, UT system allows wider openings, and CLT deep beams can give to the building a strong sense of horizontality. CLT deep beams can also vary their height and change their position relatively to floor plane, resulting in a building façade with irregular openings (figures 6, 7 and 8).

Relatively to inner spaces, the goal was to make a space as much flexible as possible, being able to answer people shifting needs and serve a larger range of people for long periods of time. This way, future changes can be simpler and more cost effective when planned for early in the design process and it can also increase a building’s longevity [4]. UT system doesn’t offers an extreme open space concept, as proposed by Michael Green with FFTT system.
however, it is also based on a heavy timber frame system in which vertical elements do not define strictly the interior space (figure 6). Keeping the discussion on inner space, façade walls can also be designed to have special shapes in order to allow structural elements to be part of space design (figures 7 and 8). 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.

Figure 6. Versatility topics proposed by UT system.

Figure 7. Different aesthetic possibilities for structural elements which compose building façade.
3. CONCLUSION

Tall buildings using CLT have been proving potential to be a well spread typology in denser cities. Actually construction of this new kind of buildings has been mainly supported by qualitative reasons, such as sustainable advantages, but there are a lot of other advantages associated to that. So, it is mandatory to promote a search for more economical solutions able to support taller buildings and more daring architectural solutions.

UT system tries to render CLT a more versatile material and more attractive to construction market. It aims to answer adequately quantitative and qualitative requests of buildings that will fill the cities of the future. Besides ecological advantages, this construction system provides a higher level of spatial and uses versatility to answer more properly the demands of today’s society. Further, it is able to answer functional requirements for a safe and comfortable building. However, some doubts still remain regarding its structural abilities.

To conclude, 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.

REFERENCES


