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STRATEGIES TO AVOID HUMIDITY CAUSING DAMAGES IN TALL TIMBER BUILDINGS

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Abstract *The number of tall housing buildings using cross laminated timber (CLT) as the main structural material has been growing all around the world but especially in Europe. This kind of construction has already proven to be a solution with a sustainable profile and despite the conflicts with some building codes and some countries legislation, this construction material is able to shape safe structures.*

However, to get the full confidence of the public, several researches focused on main CLT restrictions are still under development, such as fire safety, strength of connections, structural behavior, acoustics and durability. This last point is of huge importance considering timber's propensity for rotting and its known hygroscopic behavior. If humidity effects are not considered during the building design as well as the structure's integrity the people's wellbeing can be compromised.

The content of the present paper aims to outline important recommendations concerning the reduction of humidity causing damages in tall timber buildings. For that, CLT/glulam hybrid construction system (Urban Timber system) is used to illustrate and describe suggested construction details of a timber building, from the foundations to the roof: the most cautious solution for foundations is to resort to reinforced concrete, in case of biological attacks or unexpected hazards; facades have to ensure the protection of timber structural elements from contact with moisture either through insulation materials or by glazed walls; windows in contact with timber ends should be able to prevent water to reach them; connection between timber elements must predict swelling/shrinkage movements of timber; at least an efficient rain water drainage has to be guaranteed by the balconies and the roof design.

1. INTRODUCTION

In past few years, some innovative proposals for multi-storey timber city housing are looking for a sustainable solution for our denser cities. Cross laminated timber (CLT) is a transversal material, being the leading figure in the majority of the constructed buildings and in the proposals for new construction systems. There are monolithic construction systems that are fully based on CLT, in which CLT shapes all structural elements, some construction systems combine CLT with concrete cores and others combine CLT with linear elements made from steel and other wood-based materials.

The structural systems and materials change as the building needs more or less spatial flexibility, small or larger openings and few or more storeys. But, independent of the building needs timber construction has to prove to be safe in case of fire [1-2], earthquakes [3], to be acoustically and thermally comfortable [4-5] and be moisture resistant [6-8]. This last point is of huge importance due to timber hygroscopic behaviour. Moisture changes can cause very unpleasant effects in the building structure, such as: timber decay [9-10], building distortion/creep [11-13] and/or failure of connections [14-15].

The Urban Timber system (UT system) is a timber hybrid construction system which was developed to shape flexible multi-storey timber buildings. The present paper will use the UT system to describe and illustrate construction details which aim to prevent unwanted moisture effects.

2. TIMBER HYGROSCOPIC BEHAVIOR AND ITS EFFECTS ON CLT

Timber hygroscopicity means that it is permanently ready to release and absorb water (absorption and desorption phenomenon) when exposed to fluctuating atmospheric humidity. Fragiacomo et al. (2011) [16] calls this exposure of “humidity load”.

The shrinkage/swelling capacity of CLT is not affected regarding its width direction, however due to the crosswise arrangement and good longitudinal stability of CLT layers, shrinkage/swelling in-plane movements are reduced. Augustin (2008) [17] says that moisture movement of CLT panels is less than 1% in across the grain direction and 2% in cross-grain direction. Despite these positive numbers, the restriction of wood movement, caused by crosswise bonding of layers, can result in moisture-induced stresses and deformations (warping and checking). The experience taken by multi-storey constructed buildings, using platform framing construction, quantified an accumulative shrinkage over the height of the buildings around 3mm per story [11].

Moisture gradients are also an important moisture effect which may affect the stress of wood. This effect results from the slow moisture diffusion in wood. Wood needs long periods of time to reach equilibrium for different levels of relative humidity. Depending on the timber size, it can take several weeks or even months [18]. Moisture gradients, combined with the restriction of wood movement caused by CLT crosswise bonding induce important differences in shrinkage and swelling of wood, which will develop so-called moisture induced-stresses. According to Gereke (2009) [12], the free swelling and shrinkage of adjacent layers differs by a factor of 10 (radial/longitudinal) to 20 (tangential/longitudinal). As a consequence, serious structural damages can occur and shape distortions may reduce the serviceability. One solution to prevention is based on the drastic application of *coatings on the timber surfaces exposed to weather conditions in order to keep the moisture exchange with the environment and thus moisture induced stresses low* [19].

Wood is an organic material which needs to be protected from moisture in order to avoid material decay. Fungi are one of the biggest wood enemies. However, to perform an attack, fungi needs sufficient moisture, nutrients, oxygen, and a reasonably warm environment. Nevertheless, this kind of attack results on a reduction of the timber mechanical properties only if the same condition remains for a significant period of time [20].

3. HOW UT SYSTEM AVOIDS UNWANTED MOISTURE EFFECTS?

UT system is a proposal for a timber-based construction system, designed to shape multi-storey urban buildings. UT system offers versatility, more opening sizes, angles of facades, and free inner layouts.

3.1. Structural system

UT system is inspired in the bundled tube concept, working 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 [21].

As shown in Figure 1, CLT walls, floors and deep beams are combined together with glulam double beams. CLT walls are the main load-carrying elements which gets the loads of each floor from glulam beams and drive loads to the foundations, either through a vertical path or an oblique one. These vertical/oblique walls work also like shear walls, resisting lateral loads by being oriented perpendicular to the façades [21]. CLT floors work together with double glulam beams, 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 (a)).

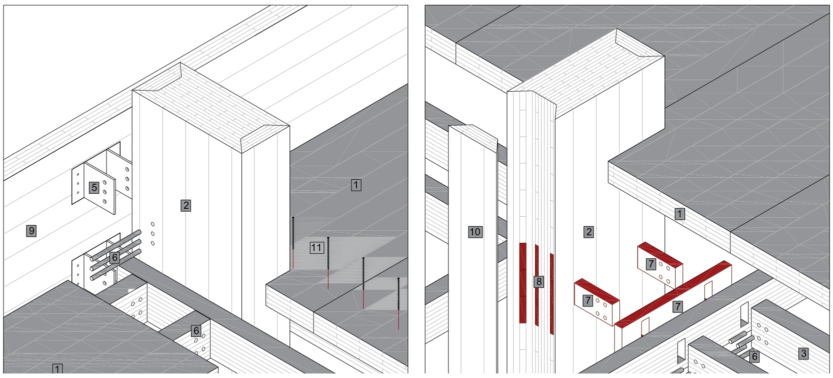
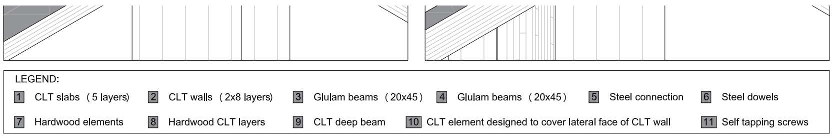


Figure 1. (a) Construction detail of structure on building perimeter walls, (b) construction detail of structure on building inner walls.



Relatively to moisture concerns, this structural system considered some essential precautions. Firstly, it is based on the balloon frame construction, choosing the continuity of vertical elements. This way, and similarly to FFTT system, the shrinkage/swelling movements of CLT floor, especially on its thickness, will not accumulate over the building height. In addition, drainage wall does not need special care to protect the lateral side of the

CLT floor. Secondly, double glulam beams are placed sideward to CLT walls and fixed to them by means of hardwood elements (Figure 1 (b)) or by steel connectors [6]. As the CLT walls will shrink/swell on its thickness direction, it is important to ensure that the connection allows the beams to follow the movement of the walls, avoiding timber crush. Thirdly, CLT floors are not fixed to CLT walls neither to CLT deep beams, but to the glulam beams in order to guarantee the freedom of movements through its thickness. This way, CLT floor shrinks/swells and does not change the building height. Fourthly, CLT walls are placed perpendicular to the façade, reducing the area of CLT in contact with external walls (Figure 1(a)). Lastly, also due to shrinkage/swelling movements, CLT deep beams have to be fixed to the top of CLT walls and not to its main face. However, it is mandatory to avoid steels connectors inserted from the outside face of the building or a water path can be created. So, a steel connector has to be inserted inside the CLT deep beam and connected to CLT wall by means of steel dowels (Figure 1 (a)).

Foundations are made of reinforced concrete in order to avoid prevention works related with subterranean termite and the use of preservative treated wood. Despite its low eco-friendly profile, concrete elements can be significantly smaller due to the low weight of the timber.

Reinforcing its preventive role, UT system resorts to reinforced concrete to shape foundations as well as underground floors and first floors. Connections between concrete and CLT walls are made 3 meters up from the ground level and is performed by a built-in steel connector, anchored in a concrete wall, and steel dowels are used to fix the CLT wall. If the exposed concrete is not an attractive option for the designer, concrete walls can easily be covered with timber boards, thus obtaining a final look similar to CLT.

3.2. Facades

Despite the significance of the building envelope on its energy efficiency, indoor air quality and occupant comfort, a special attention has to be given to durability when it comes to a timber building design. It is essential to control water intrusion, air flow between the interior and the exterior as well as water vapour diffusion.

UT system places structural walls perpendicular to the façade, in order to protect CLT panel from different environments: (I) when UT system considers a rain screen system, the CLT wall is entirely on the inside environment while CLT deep beams are the elements that make the border between the interior and the exterior (Figure 2 (a)); (II) when it is considered as an external continuous glazed curtain wall, the entire building structure is the inside environment (Figure 2 (c)); (III) when balconies are considered in the entire perimeter of building, the CLT wall is almost entirely on the outside environment (Figure 2 (b)); and (IV) when it is considered a double glazed curtain wall, CLT walls and deep beams are placed in an intermediate environment (Figure 2 (c)).

So, UT system proposes four different possibilities for façade drainage, depending on the chosen result for the appearance of the façade. Two suggested possibilities require a rain screen system, one of the most efficient solutions for multi-storey buildings [8]. However, considering CLT hygroscopic behaviour, the building enclosure has to create an efficient vapour permeable wall set. As depicted in Figure 2 (a and b), besides the main drainage plane, created by exterior cladding, two extra drainage planes are created: a gap between exterior cladding and insulation layer and a vapour permeable and water resistant barrier applied directly to CLT surface. This way, the water that passes through the exterior cladding, will find other two drainage planes that will drain away all moisture from the façade of the building before it reaches the CLT elements [11]. Further, a wind barrier is placed in the gap between external cladding and insulation layer, as recommended by [22]. This same gap should be ventilated, though openings at the top and bottom of the wall assembly, in order to assure the drying of materials. External cladding is fixed to a threated wood strapping, which in turn is fixed to a CLT panel with compatible corrosion resistant long screws through the insulation layer. This last one has to be rigid enough to avoid compression when screwed and water resistant in order to quickly drain the water away from the building. Examples are: extruded or expanded polystyrene, mineral wool [11, 23] and cork [24].

According to Glass et al. (2013) [11], uncontrolled air leakage can cause moisture accumulation and interticial condensation and, consequently, CLT decay besides other problems related with the building's energy performance, the indoor air quality, and comfort of the occupant. It is recommended a vapour permeable and water resistant barrier. It will prevent that moisture causes effects on the CLT elements as it will also allow the drying of the construction. Vapour permeable materials are desirable for all wall sets in order to guarantee the desirable drying capability of the entire assembly.

The other two possibilities that the UT system proposes are based on the glazed curtain wall concept. Both solutions make the entire structure waterproof, avoiding all cares related with CLT durability and the building envelope design. Further, depending on the structure for curtain wall attachment, CLT deep beams can be avoided, turning the building completely transparent. However, in a glazed curtain wall solution, instead of moisture, CLT has to deal with temperature issues. Furthermore, larger openings reduce thermal and acoustics benefits, forcing the use of high performance windows, able to improve energy efficiency, reduce heat gain and loss, reduce noise levels, reduce condensation and improve comfort [8].

3.3. Balconies

CLT is a material that is typically produced with untreated softwood species, which predisposes it to decay when it remains wet for long periods. Balconies are structures with a high propensity for undesirable water intrusions and accumulation. As such, secondary structures are often created in order to separate the building and balcony structures: cantilevered prefabricated steel structures [25-26] and balconies with independent structural frame and foundations [11].

The UT system presents one single proposal that contains external balconies (Figure 2 (b)). These balconies are covered and not cantilevered, trying to minimize thermal and durability problems. The biggest problem related with CLT balconies have to do with the risk of water intrusion, which means that is required a special care on its design and execution. A balcony has to be finished similarly to a low-slope roof, which is described ahead in the text. Despite the careful design, the UT system suggests the separation between the inner floor and the outer floor elements, instead of a single CLT plate shaping both. This way, an unexpected infiltration does not cause major damages on inner floor assembly while outer CLT plates can easily be replaced.

The problematic point of the proposed assembly are the glulam beams, which support both CLT floors. One solution is the application of water repellent into the parts of the glulam beams which support the balcony floor. However, further research is required in order to improve this solution.

The proposed solution with balconies also adopts the rain screen system for facades. Although CLT deep beams do not directly affect the thermal behaviour of the building, the insulation layer is continuous all around the building perimeter and balconies. This way, thermal bridges through balcony structures are not a problem.

3.4. Windows

The main concern related with a window assembly is the maximum control of the water path. As mentioned before, the UT system suggests four solutions for openings, which vary according to the size of the windows, its location and support.

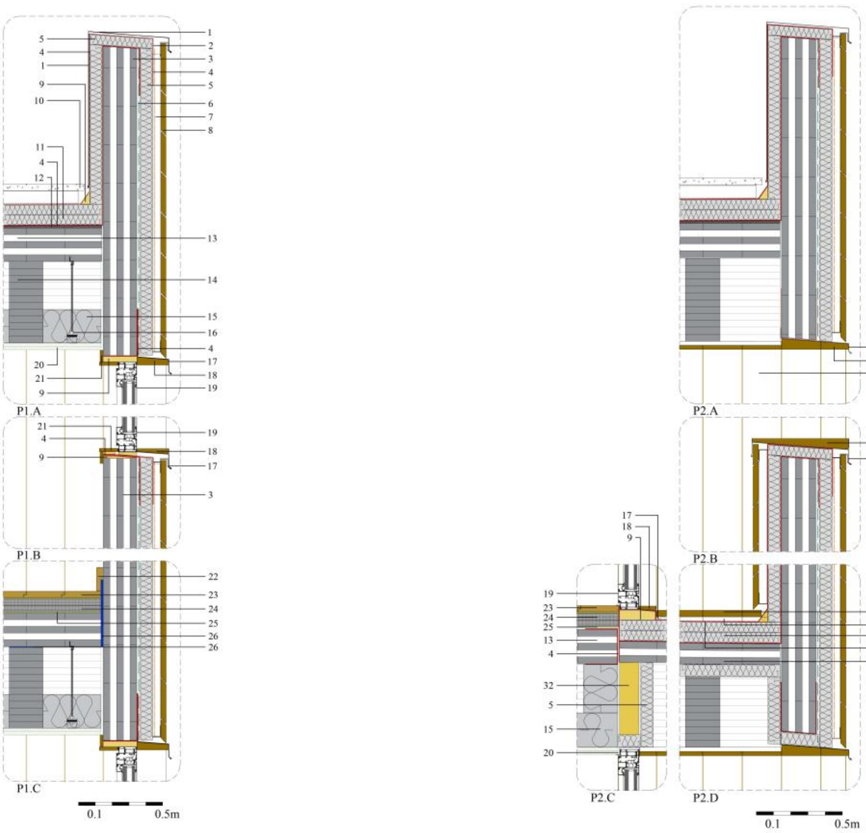
The first solution which places the windows aligned with the rain screen facade (Figure 2 (a)), proposes wider windows, which are supported on CLT deep beams. As recommended for CLT construction, the exterior side of the window assembly is placed in the same plane of the vapour permeable water resistant membrane [11]. The water is prevented from entering the building by means of a sloped metal flashings with end dams, located up and bellow the window. To keep water away from the window sill, CLT deep beams are finished with a sloped timber shim which is covered with two self-adhered membranes that must be water resistant and vapour impermeable. The first membrane overlaps the vapour permeable water resistive membrane while the second one overlaps the insulation layer.

The glazed curtain wall is a completely different solution, composed by glass panels, opaque panels and/or operable windows, attached to a frame supported by a building load bearing structure. The efficiency of these kind of solutions, relatively to water/air infiltration, is based on the quality of the gasket and the sealant material, as well as on the proper installation. Furthermore, air tightness can lead to undesirable indoor air quality problems, supplying moisture enabling the slow growth of mold. Generally, these kind of assemblies also require special attention regarding the building's thermal behaviour. That is why thermal glass is a frequent choice. But, the gain on thermal performance can lead to undesirable moisture problems derivative from the condensation effect [27]. Figure 2 (c) shows a simple solution, with a timber frame (Uniglas ®), in which glass panels are glued to small timber ribs that are screwed to the timber frame.

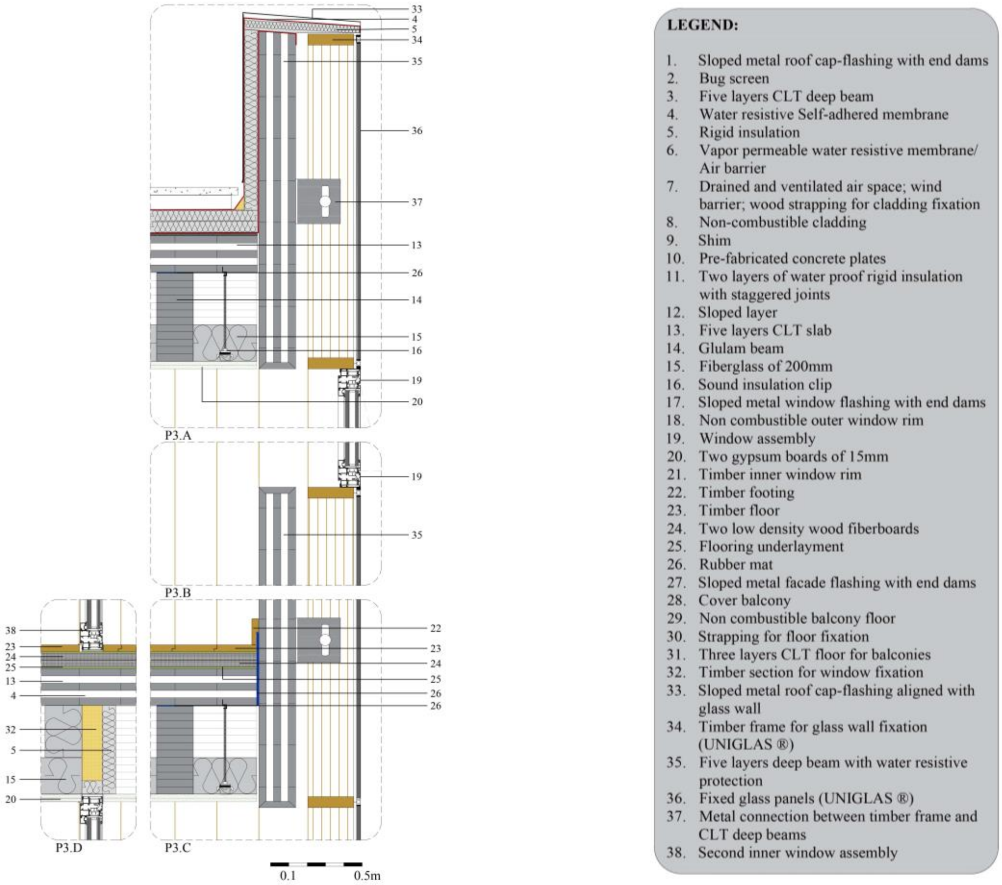
The third proposal places balconies in the building perimeter (Figure 2 (b)). This way, window assemblies are protected from rain through the balcony structure, which means less possibilities of water infiltration. The difficulty of this solution is related with the drainage of the balcony floor, which will prevent water accumulation and consequent water infiltration inside the building. Despite the window assembly being inside the wall assembly, the opening in the facade remains the same. So, sloped metal flashings are also placed on the top and bottom of the opening, in order to keep water running through the external cladding and the tops of CLT deep beams are also protected with water proofing membranes. The balcony floor (similar to a low-slop roof assembly) meets the inner window assembly by means of two water proofing membranes, which protect the inside from accumulative water, and a metal flashing, which makes the water from the windows to run through the balcony drainage. The last proposal, based on the concept of a double glass wall (Figure 2 (c)), applies the glazed curtain wall system to the building limit and adds a second glass layer inside the building, creating inner balconies. The advantages of this system compared with a single glazed curtain wall are essentially related with a better thermal behaviour and with the possibility of natural ventilation. These two glass layers improve the insulation and condensation control. These inner balconies help to preserve energy, by balancing interior and exterior temperatures, either during cold or warm seasons [27].

3.5. Roof

UT system fits with the aesthetics of low-slop roof assembly which, despite its higher propensity for water accumulation, does not need much more care than concrete structures. A conventional solution for a concrete low-slop roof is: application of a sloped layer; placement of water proofing membranes over the entire roof surface and bypassing parapet flashing, position of rigid insulation and sealing its joints to reduce air flow and avoid water penetration, and floor assembly for accessible roofs and for radiation protection.



(a) (b)



(c)

Figure 2. Construction details for different proposals to UT system facades. (a) rain screen wall assembly; (b) rain screen wall assembly with balconies; (c) glazed curtain wall.

Extra cares related with CLT roof assemblies are: adding another layer of water proofing and vapour resistant membrane on the top of insulation layer and ensure the removal of water accumulation near the roof-wall intersections. This last one is made by the placement of a sloped shim placed in the roof-wall intersection (Figure 2).

Some other solutions for low-slop CLT roofs have been suggested, such as: application of closed-cell spray polyurethane foam insulation directly over a membrane on the CLT and covered with a polymeric top coat for UV protection [11]; the creation of a ventilation gap, similar to rain screen wall system that allows materials to dry easily [25-26].

4. CONCLUSIONS

Present paper outlined some essential recommendations to reduce humidity causing damages in tall timber buildings. It was described the UT system, a CLT/Glulam construction system which considered timber hygroscopic behaviour to define the position and connection between structural elements. The same system was used to illustrate four different solutions for effective facades, including: rain screen wall, glazed wall, rains screen wall with balconies and double glazed wall. A solution for low slope roofs was also discussed.

Future work will focus on recommendations about moisture cares related to: wet rooms walls and floors; water pipes insulation; plumbing, mechanical, electrical and structural penetrations; and inner dry wall assemblies.

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