PREFabricated CLT Façade Systems for Fast-Track Construction and Quality Assurance

Eugenia Gasparri¹, Giorgio Giunta⁴, Enrico Sergio Mazzucchelli³, Angelo Lucchini⁴

ABSTRACT: Prefabrication of timber envelope components is a constantly developing research field, which attracts interest from various sectors of expertise thanks to the conspicuous advantages it can confer in terms of resources savings, as well as quality management and safety for all actors involved in the process. The present paper goes through the design of a newly conceived external wall system for tall CLT buildings, entirely preassembled off-site and so able to be installed on his final position via crane, renouncing to scaffolds for the façade completion. This not only allows for the construction phase to speed up but also for immediate protection of load-bearing timber elements from weather agents exposure. The work follows three main phases: the functional analysis and layer definition, component design through bi-dimensional study of joint operating mechanism and tri-dimensional validation of the system. Main author findings outline how success of prefabricated systems and their durability over service life is strongly dependent on the effectiveness of joint design.

KEYWORDS: CLT constructions, load-bearing façade system, design process, technical details, off-site prefabrication

1 INTRODUCTION

In the recent years, cross-laminated timber (CLT) has been gradually spreading across the market as a valid technology to be used for the realization of multi-story buildings [1]. This is due to the advantages it offers from very different points of view, such as structural performance, seismic behaviour, environmentally related benefit (CO₂ storage) and on-site time savings [2]. Anyway, this latter involves only the realization of the structure, while the completion of the envelope requires a much longer phase [3].

In fact, envelope extensive prefabrication can represent a significant opportunity for CLT constructions, especially for tall buildings where longer construction times can lead to the risk of incurring in unfavourable weather conditions. This is an issue of outmost importance, in the case of timber construction elements, for two main reasons:

• weather changes can strongly affect the overall on-site process quality leading to double site work delay, related to the actual physical phenomena that can cause work interruption and also due to the need for timber components drying. In addition, engineered wood products require longer times to dry [4];

• adverse weather conditions during construction can affect the building service life as well as causing problems related to incorrect humidity levels, such as mould. In addition, moisture content variation can also cause swelling and shrinkage of wood, which represent a major critical issue in the case of tall wood buildings [5].

Figure 1: Façade element prefabrication in the production factory. Source: www.binderholz.at

An additional strength in favour of an extensive use of prefabrication is the fact that most of weather shielding devices commonly integrated in construction sites are not able to guarantee adequate protection to building components. Also, if temporary roofing structures are

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applied, they may be effective but this advantage is counterbalanced by long realization time and high cost [6]. Despite timber frame technologies have already a tradition related to off-site preassembly of components, both in the case of infill or structural elements for small buildings, the field of load-bearing elements prefabrication for tall buildings is way more complex and rather unexplored so far.

1.1 AIM AND SCOPE

The research work presented in this paper deals with the design of Prefabricated External Wall (PEW*) systems based on load-bearing supporting CLT technology that are suitable for tall buildings and allow for fast-track construction and quality assurance [7]. Prefabrication degree has to be intended as the maximum possible one, that is to say including all the functional layers located on the outer face of supporting structure, such as insulation, tightness membranes and external cladding. This is necessary to avoid any work from outside but allowing to operate from the inside of the building in dry conditions. Within the frame of this research, tall building definition applies to more than eight story high constructions, when scaffold installation becomes quite an issue both from a structural and safety point of view (see Figure 2).

Within the frame of this paper, structural concerns deriving from the presence of a CLT support layer are not described in detail, as they fall out of the scope [7,8]. Only building physics control functions affecting significantly system definition will be detailed, such as:

- waterproofing;
- air flow control;
- insulation.

2.1 CROSS SECTION DEFINITION

The first barrier against water encountered from the exterior is the so called water-shedding surface (WSS) [9]. This is the outer surface of a wall assembly, whose task is to deflect and drain the majority of water impacting the façade plan. It can be designed in two different manners: either it can be installed in continuity with interior layers or including an air gap between cladding and the rest of the wall assembly. For the proposed solution, ventilated rainscreen has been considered the most appropriate solution to prevent external wall assembly surface from wetting and at the same time allow for higher flexibility under the architectural point of view. This last concept might also allow for better integration of joint horizontal and vertical gaps occurring at the interface of façade prefabricated elements, thanks to the possibility to arrange cladding element distribution, spacing and orientation.

The second protection plan against water penetration is the water-resistive barrier (WRB) [9]. This is the main water-tightness layer, which must prevent water passage from the exterior to the inner layers of the wall assembly. In the case of CLT construction, this is generally applied by manufacturers on the external side of timber panels or by contractors immediately after erection on-site. It must be made of a vapour-permeable material in order to permit natural hygrothermal regulation during building service life. Within the frame of this work, WRB is located on the external side of the wall assembly instead of directly applied to cross-laminated timber panels, conversely to the common know-how related to timber construction. This is due to the fact that external walls arrive at the construction site already preassembled, thus cross-laminated timber is protected from atmospheric agents immediately after its installation, independently from the positioning of WRB. Air flow control is a topic of the utmost importance when dealing with building enclosure design as it can dramatically influence the whole building energy performance and be responsible for interstitial condensation phenomena as well [9]. Air flow is usually controlled through the application of several materials working as a system to satisfy the same function. When dealing with prefabricated façade it is fundamental that these materials are able to accommodate movements at panel interface, to avoid air leakage during building service life. Within the development of this research, joint air tightness is a crucial point and will be illustrated more in detail in section 2.2.

Thermal performance of a wall depends of course on material properties it is made of, but also design choices about reciprocal layer positioning can be of utmost
relevance. It is known that wood performs considerably better in terms of thermal insulation than other building materials like concrete, steel and glass, and this can be a great advantage in those locations where thermal bridges are more likely to occur, such as balconies [10]. In addition, when considering mass timber technology, wooden support panels inherently offer a nominal amount of thermal resistance (in softwood species R-value is around 0.09 m²K/W for each centimetre material thickness), allowing for thinner insulating material layers and so reducing the overall wall thickness. This is particularly convenient when prefabrication is involved. Italian building regulation assigns different U-value limitations according to specific geographic locations. The presented panel cross-section is based on a 10 cm thick rock wool insulation (λ=0.035 W/mK) but several R-value options are presented in Table 1.

Table 1: Rock wool required thickness to match regulatory standards (Italian and Canadian cases), according to various CLT wall thicknesses

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<thead>
<tr>
<th>CLT thickness [cm]</th>
<th>ROCK WOOL thickness [cm]</th>
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<tr>
<td>10</td>
<td>3.8</td>
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<tr>
<td>12</td>
<td>3.2</td>
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<td>14</td>
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<td>16</td>
<td>1.9</td>
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The issue of prefabrication needs has also driven the choice of insulation material for the proposed façade system as well. In fact, rock wool insulation provides high level of thermal performance in a relatively thin space and, furthermore, it has a reduced weight conversely to wood-based insulation products. These characteristics help to ease transportation and handling phases of prefabricated façade elements, avoiding weight related limitations to panel total dimensions. Synthetic insulation products do not match well with timber systems, even if they are really light weight and well performing because they are not permeable and may trap moisture. This is particularly risky in heating dominated climates. Finally, insulation placement may significantly affect durability and performance of the overall system. The proposed technical solution is based on external insulation to keep wood dry and warm, and minimize moisture damage related risks.

Vapour diffusion control layer was not considered when defining the proposed cross-section as it may be not needed within some climates or assemblies, particularly considering the fact that CLT acts as a buffering element with regards to hygroscopic balance of indoor environments. Moreover, it is typically placed on the inner side of the wall assembly and so it is not necessary to preassemble this element offsite. All of the above consideration led to the definition of some cross section options, selecting Figure 3 as the one which better conjugates advantages for thermal bridges limitation at panel edges and installation optimization. This can be considered the base panel where the installation of several types of external cladding was studied and designed to be installed at the production site or eventually at the foot of the building before lifting for installation.

Figure 3: Base panel horizontal cross section (out-of-scale)

1. Cross-laminated timber, ρ= 470 kg/m³
2. Timber transom, sec. 50 x 100 mm, ρ=510 kg/m³
3. Double density rock wool insulation panel, λ=0.035 W/mK, th. 100 mm, ρ=70 kg/m³
4. Synthetic breathable 3-layer membrane
5. Insulation plug
6. OSB element for panel frame reinforcement, th. 12,5 mm, ρ=620 kg/m³

The choice of using exclusively timber products derives from a marketability consideration for the designed system. In fact, limiting the use of non-wooden products reduces the number of players during the manufacturing phase, consistently simplifying the whole process both under the technical and commercial point of view. The study concerning the top and bottom interfaces between façade panels is particularly complex due to the contemporary presence of floors. The detailed investigation on this matter will be presented in the section 2.2.1.

2.1.1 Cladding options

External cladding has functional tasks related to building physics and characterizes the aesthetic appearance of a specific building. General design criteria involve several parameters, such as surrounding context, building geometry, climatic conditions, client and designer needs and maintenance requirements. That is why the adopted design approach aims to satisfy different project demands relying on a base panel that applies to all cases and a specification of cladding systems that can be equally adapted to the base. A variety of cladding materials, shapes and technological systems have been studied in cross-section to demonstrate their suitability for installation on the proposed base panel in order to allow high levels of architectural composition and flexibility (see Figure 4). They differ for:

- substructure, that can be wood-based or metallic. The latter allows for more accurate regulations in the three directions of space and for this reason it is preferable in the case of large or tall building envelopes;
- fixing system, that is to say passing-through and clips (exposed or concealed). Both of them tightly retain cladding elements while allowing for dimensional changes up to a certain extent. Conversely, gravity
based retention systems cannot be used in the case of entirely prefabricated façade elements as transportation and handling phase could easily cause cladding breakup or misalignment.

• finishing material, including wooden planks arranged both horizontally and vertically, cement fibreboard, high pressure laminated plastics, porcelainized ceramics, photovoltaic glass and metal sheets. They do not cover all possible cases but are intended to provide clear indications on customization possibilities.

Technical detailing presented in the following sections will integrate wooden cladding, for the sake of presentation simplicity. However, it is important to state that its correct use and application requires in-depth knowledge of material properties and exposure conditions, together with regularly planned maintenance to avoid precocious decay.

The first step involved the evaluation of the most appropriate location for horizontal joint positioning with respect to the structural wall-floor interface. This was performed considering different parameters, such as system vulnerability with respect to transportation and installation procedure, operational quality for workers and air/water tightness related issues (see Table 2).

More in detail, when building façade joint is located at the intrados of floor level, wall panels will have a projecting part, which is definitely the most vulnerable one, located at the bottom (see Figure 5, j.3 option). This implies that it is in a potentially vulnerable position as far as transportation and installation phases are concerned. On the other hand, air and water tightness can be more easily solved if compared to other options, such as joint locations at the extrados or in the middle of the floor edge. In fact, the bottom wall-floor joint can always be solved through the extension of the air-tight membrane towards the floor edge. In addition, the top wall-floor joint can be protected by the presence of the upper wall assembly projecting part.

If the building façade joint is placed in the middle of the floor thickness as in option j.2, panels will have two projecting parts on both sides. The same considerations of the previous case also apply to this case, except for vulnerability that is higher in the latter as the projecting parts are doubled in number.

### Table 2: Rating system for horizontal joint definition

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<th>j.1</th>
<th>j.2</th>
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<tr>
<td>Vulnerability</td>
<td>***</td>
<td>*</td>
<td>**</td>
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<tr>
<td>Operational quality</td>
<td>***</td>
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<td>*</td>
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<tr>
<td>Joint reliability</td>
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Note:
* Less favourable | ** Average | *** Most

When the building façade joint is placed at the extrados of floor, wall panels will have the projecting part located at the top, as seen in option j.1. This time standing transportation of panels can be done without particular concerns, as well as installation procedures are less critical. Furthermore, workers can act for joint completion at the level of the just installed floor, so they do not need to lean out of the floor edges and can perform their tasks in more convenient conditions. Despite this, air and water tightness of this option could become quite an issue at the level of top joint as the air
flow path is not tortuous and water may infiltrate under particularly harsh wind conditions. Given all the above considerations, placing panel horizontal joint at the level of floor intrados was the preferred alternative (j.3). In fact, joint reliability concerning tightness functioning has been considered the leading parameter for the value analysis.

**Figure 5:** Joint positioning options with regard to floor – Base panel vertical cross section (1:10)

1. 2. 3. 4. See Figure 3
5. OSB element for panel reinforcement, th. 12, 5, $\rho=620$ kg/m$^3$
6. Timber transom for pin cladding substructure constraint, sec. 50 x 100 mm, $\rho=510$ kg/m$^3$
7. Sloped timber transom for panel framing and reinforcement, sec. 50 x 100 mm, $\rho=510$ kg/m$^3$
**Figure 6**: Interface joint detailing in the case of vertically oriented wood planks cladding – horizontal (left) and vertical (right) section (1:10)

1. 2. 3. 4. See Figure 3
5. Vented wall fir wood mullion, sec. 70 x 35 mm, $\rho=510$ kg/m$^3$
6. Vented wall fir wood transom, sec. 20 x 50 mm, $\rho=510$ kg/m$^3$
7. External cladding: vertically oriented fir wood planks fixed
11. Metallic sill
12. Metallic flashings for window jambs
13. Acoustic rubber insulation mat
14. OSB element for panel reinforcement, th. 12, 5, $\rho=620$ kg/m$^3$
15. Low density rock wool insulation panel, $\lambda=0,035$ W/mK,
2.2.2 Vertical joint

The definition of vertical panel joint has been carried out, firstly, by determining the structural joint between CLT adjacent support layers. The connection is realized through the insertion of a single surface wooden strip, which can be installed from the inside of the building. In fact, other common alternatives as the half lapped joint showed some criticalities, forcing a rigidly sequenced installation for façade panels.

Air and water tightness are completed through the on-site installation of complementary vertical flashing, tight membranes and the use of compressible acoustic insulation mats at the interface between CLT panels, that helps in preventing air fluxes inward and outward. An additional linear developed insulation element is placed between wall panels on the external half of the joint to interrupt thermal bridge. This latter has to be sufficiently soft in order not to transfer loads between adjacent façade elements. The horizontal section with all main interface detailing joints is presented on the left side of Figure 6.

2.2.3 Installation sequence

Before going into detail of panel installation description it is important to notice that construction practice is meant to be developed one floor after the other, according to a wall-floor-wall sequence. In these cases, it may be a convenient option to leave a vertical strip free of panels until the end of construction work to allow for the passage of building components, for instance system parts and machines, or interior finishing materials. Installation is carried forward according to the following phases:

a. Erection of load-bearing wall system at a certain floor, including external prefabricated wall assemblies;

b. Subsequent upper floor installation, to create a work platform for the level above;

c. On-site horizontal joint completion from the just installed floor: final positioning of water tight membrane from lower wall panels at the floor level in order to solve the bottom joint; metal flashing installation along the building perimeter and placement of an additional stripe of airtight membrane on the external side of the flashing element, to protect timber close to the presence of passing through screws. The flashing has the task to drain water falling down from behind the cladding, creating a continuous water barrier and drainage system at floor interfaces. It can be concealed behind the cladding system or span outside the façade plan, creating a floor mark. Low density insulation is placed in front of the flashing to eliminate thermal bridge at the floor edge;

d. Acoustic mat installation ready to receive the upper façade assembly;

e. First upper wall prefabricated element installation from the working floor;

f. On-site vertical joint completion through flashing and insulation installation on one side of the already fixed panel;

g. Lifting of adjacent panel to working floor and complementary flashing installation on panel side;

h. Panel juxtaposition, adjustment and fixing;

i. Subsequent iteration of the previous three phases until completion of the opaque building perimeter for the working floor.
Detailed installation sequence for joint components is shown in Figure 7 and Figure 8, respectively for the vertical and horizontal section. In the case of the present research work, external wall panel continuity is interrupted at the level of floors as a design choice (platform frame configuration). However, the same considerations made in this section also apply to the balloon frame technology, with the sole difference that this latter does not suffer from compression perpendicular to grain on floor edges [7].

2.3 3D-MODEL SYSTEM VALIDATION

The elaboration of 3-dimensional models when creating a new construction system is fundamental to ensure error-free fabrication and smooth on-site installation. In addition to this, precise drawings will be required both by manufacturers and contractors in order to identify project criticalities and solve them before the building construction starts. Finally, advanced fabrication machines are controlled by numerical files generated by executive design projects, so a 3-dimensional manufacturing model has to be produced at some point of the industrial process.

More specifically, the objective of the 3D design phase in the frame of the present research work was manifold:

- verifying component installation procedures (see Figure 9);
- outlining different marketability options for the system to be customized by client and designers (a representative case is shown in Figure 10);
- validating the correct drainage mechanism and overall functioning of joints at the encounter of multiple façade components, to gain awareness of all water possible paths once it overcomes rainscreen barrier.

3 THE PEW+ SYSTEM: FUTURE PROSPECTIVES

Foresights in the use of unitized wood-based façade assemblies for tall buildings are shortly presented within this section, to provide evidence of timber innovative application potential, which take a distance from the traditional craftsmanship approach to construction. In fact, another joint configuration has been studied in detail with the aim to broaden both timber façade and CLT field of applicability, fitting well also in the case of office buildings [7]. The design approach is based on pressure equalization principles through the use of a gasket system integrated on the base panel frame, whose task is to create a series of decompression chambers, where water that overcomes the first barrier is blocked and drained towards the exterior. This method is also used for unitized glazed façade systems, widely spread nowadays in the case of high rise building envelopes for two main reasons: they are amongst the most weather resistant and air tight prefabricated technologies on the market, and they allow for high efficiency in installation.

In this way, the newly born unitized wood-based façade system proposed can be easily integrated with plug-and-play unitized glass façade modules, providing higher degree of architectural freedom and appealing design opportunities (see Figure 11).

Many other ideas can be inspired by this, for instance the design of non-load-bearing CLT or timber-frame façade systems, which being free from the task of vertical and horizontal load transmission can be placed differently.
with respect to floors and adapted to different structural systems, such as steel or concrete frame.

Figure 11: Glass and wood-based unitized façade integration – detailed (left) and global (right) view

Figure 12: Examples of integration between opaque concrete based prefabricated façade and unitized glass façade (University of British Columbia campus, Vancouver)

4 CONCLUSIONS

Study and development of an innovative wood-based prefabricated wall assembly has been presented in this paper as far as its technical requirements and performance are concerned. The work makes a step further in the field of timber construction, introducing a load-bearing entirely preassembled external wall system with CLT supporting structure, which can be installed in its final position without requiring further work from outside. Moreover, it is characterized by high degree of standardization as far as off-site fabrication is concerned despite offering consistent customization opportunities. This is guaranteed by the development of a base wall assembly, that can be integrated with a wide range of cladding options equally installed during fabrication or on the construction site before panel lifting. Several finishing materials and fixing systems have been studied and integrated on the base panel to give evidence of some customization possibilities, provided that many other alternatives are applicable.

The focus of the design process is panel joint study and definition, so to be easily installed on-site and provide the possibility to complete the whole building envelope without the need for scaffolds, which was one of the main objectives of this research. The design approach is based on the use of tortuous paths at panel joint and overlapping tight membrane to inhibit air leakage and water infiltration. Project development was validated through the set-up of a 3-dimensional digital model, which proved the effectiveness of the designed façade system. This phase had the aim to check correct functioning of water and air tightness at panel interface and prove constructability of prefabricated modules. Limitations of this research are due to project budget constrains resulting in the impossibility to execute laboratory air and water tightness testing on a real scale mock-up model. This is a fundamental step in order to assess the performance of a new-born prefabricated system, and further research effort will be devoted to this in the near future.

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