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Review of the Performance of CLT Wall-To-Floor Connections for a Multi-Storey Modular Building using Irish Timber

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ABSTRACT: In recent years, the focus has shifted toward more sustainable construction methods. Cross-laminated timber (CLT) has emerged as an excellent material in terms of structural properties and environmental impact. Across Europe, C24-grade timber is primarily used for the manufacture of CLT and hence most of the research data available is for CLT of this grade. However, Ireland has an increasing supply of C16-grade Sitka spruce timber and studies have shown that C16-grade Irish timber is suitable for use in CLT. This paper reviews the commonly available connectors for wall-to-floor connections in CLT and their feasibility and functionality for a multi-storey modular building constructed using C16-grade CLT. A modular building consists of stackable and scalable prefabricated modular units which are manufactured off-site and transported and assembled on-site. The most common types of commercially available connectors have been reviewed and angle brackets have been identified as the most common type of connectors for wall-to-floor connections. Numerical modelling of these connections to predict their behaviour under shear and tension loads has also been reviewed. Future research needs for using these connections for a modular building made of C16-grade CLT have also been identified and highlighted.

1. INTRODUCTION

Due to the increased focus in construction toward more sustainable construction methods, Cross-Laminated Timber (CLT) has emerged as an excellent construction material in terms of structural properties as well as environmental impact. CLT has a high strength-to-weight ratio, which is a major contributing factor to its increased popularity as a sustainable choice of construction material in several countries across Europe, North America and Australasia. Ireland has an increasing supply of Sitka spruce, which is a fast-growing species that yields relatively low-density timber. This timber is primarily graded as C16-grade timber as per EN 338 (CEN 2016) (O'Ceallaigh, McGetrick, et al., 2021). However, the timber grade which is used in construction across the rest of Europe is typically C24-grade timber. As such, the data and literature regarding connections in CLT construction are mainly available for C24-grade timber. This paper aims to review the most commonly used connections in CLT construction, with the main focus on wall-to-floor connections which will aid the design of a multi-storey modular building constructed using C16-grade CLT.

Modular construction is a modern method of construction which is found to have significant advantages over traditional methods of construction. In modular construction, the modules or units are prefabricated in a factory, which leads to a high degree of accuracy, better quality control and faster construction times. These scalable and stackable modules are assembled on-site to make up the modular building resulting in a relatively rapid means of construction.

The volumetric CLT unit examined in this paper is a standard 3-D rectangular cuboid shape. The prefabricated CLT panels are arranged and connected to form the volumetric modular CLT units. The design also considers a lifting connector solution so that the modular units can be lifted from the factory to transportation vehicles. At the site, connections are required to connect the units together and connect the units to the substructure to contribute to the overall stability of the building and provide a load transfer pathway to the substructure. The installation of mechanical and electrical services also impacts the location and type of panel-to-panel connections that can be used and must be considered at the design stage.

This paper reviews the different types of wall-to-floor connections available and the most suitable connections are discussed in respect of deconstructability, scalability and expected load capacity.

2. WALL-TO-FLOOR CONNECTIONS

2.1. Construction Methods

Typically there are two methods of construction using CLT. These are namely, platform framing construction and balloon framing construction, which are shown in Figure 1 and Figure 2, respectively.

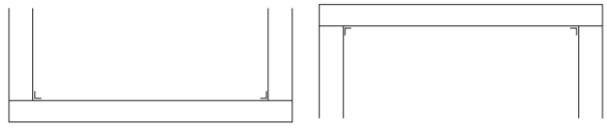

Figure 1: Platform framing construction.

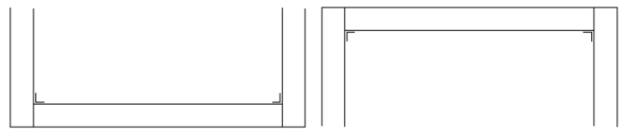

Figure 2: Balloon framing construction.

In the platform framing arrangement (Figure 1), the CLT wall panels sit on top of the CLT floor panels and below the ceiling panels, creating a workable platform. Platform construction is widely used for low-rise buildings. However, with the increase in building height, there is an increase in the compressive force in the direction perpendicular to the grain, transferred from the walls above to the floor below (Harte, 2017). The excessive deflection due to this force may be transferred to the wall below by using self-tapping screws or other steel connectors (O'Ceallaigh, Conway, et al., 2021). Alternatively, the balloon framing arrangement (Figure 2) can be used to avoid the issue due to high compressive forces perpendicular to the grain. In balloon construction, the walls are continuous from floor to floor and the ceiling and floor panels are supported and connected to the side of the walls through the use of self-tapping screws and bracket connectors. This connection is designed to support the vertical loads from self-weight and imposed loads acting on the floor or ceiling.

2.2. Typical CLT Connection Systems

Connections are designed to resist vertical loads due to gravity as well as horizontal loads due to wind and seismic action. The most commonly used connection system for CLT wall-to-floor connections are angle brackets for shear and hold-downs for overturning. An example of a typical angle bracket can be seen in Figure 3.

Blaß & Uibel, (2007, 2013) developed some of the first analytical models for the design of such CLT connections using screws, nails and dowel-type fasteners, and their model is used by researchers to compare with their experimental data.

Figure 3: Rothoblass angle bracket (Rothoblaas, 2017).

Gavric et al. (2015a) conducted a study on screwed wall-to-floor CLT connections subjected to in-plane monotonic and cyclic shear and withdrawal tests. The experimental results were compared using analytical design equations from Eurocode 5 (CEN 2005b) and Uibel & Blaß (2007, 2013). The screwed connections performed well under cyclic loads when ductile behaviour was achieved. Brittle failure is observed where edge and end distance criteria were not met. Bratulic et al. (2014) studied the wall-to-floor CLT connections with self-tapping screws subjected to monotonic and cyclic loading. Tests were carried out using fully or partially threaded screws inserted at 90° and 45° angles. The results were compared with analytical models according to Johansen's yield theory and Bejtka & Blaß (2002).

Ceccotti et al. (2006, 2010, 2013) performed an extensive series of tests on commercially available CLT connections as a part of the SOFIE project and found that the behaviour of a CLT wall system is governed by connection behaviour. The panels were tested under monotonic and reversed cyclic loading. Standard hold-downs and angle brackets were used in different configurations with annular ringed shank nails and screws for fastening the steel connector to the CLT panels. It was found that stiffer connections have higher load-carrying capacity but lower ultimate displacement and less ductility. The CLT panels remained rigid and the energy dissipated occurs in the connections. Subsequently, a full-scale 3-storey and a full-scale 7-storey building were designed per Eurocode 8 (CEN 2005a) and tested for seismic loads using a 1D and a 3D shaking table respectively. Ductile failure modes were observed in these buildings with fastener bending and embedment. Gavric et al. (2015b) studied the cyclic behaviour of CLT wall systems with typical connections. Angle brackets were used to resist shear and hold downs were used to resist overturning. However, it was found that angle brackets are also capable of resisting tension forces, but hold-downs did not exhibit significant shear strength. D'Arenzo et al. (2018, 2019, 2021) developed an innovative angle bracket connection to resist both shear and tensile forces. These novel Titan V (TTV) brackets used fully threaded screws to improve the mechanical properties for tension.

While there has been a significant research focus on this area in recent years, most of these connections were tested for C24-grade CLT panels and a limited number of studies have focused on C-16 grade material. O'Ceallaigh & Harte (2019) examined the behaviour of steel-to-timber bracket connections using C16-grade CLT. The connections were subjected to monotonic and cyclic loading and were tested for various screw lengths. The experimental values were then compared to analytical models using the provisions of Eurocode 5 (CEN 2005b) and the analytical model presented by Uibel & Blaß (2007, 2013) and were shown to perform well when applied to C16-grade material.

2.3. Connections in the MODCONS project

In parallel to this paper, the MODCONS project (www.universityofgalway.ie/terg/modcons/) at the University of Galway involves the design of a 7-storey modular mass timber building designed as per Eurocode and Irish Building Regulations. The case study modules are designed using C16-grade CLT panels and using a volumetric construction approach for ease of construction and deconstruction. Balloon framing arrangement is chosen as the method of construction as it provides better quality control from the manufacturing aspect in addition to addressing the issues due to high compression loading perpendicular to the grain.

Self-tapping screws can be used for wall-to-floor connections, either with angle brackets or with a timber plate or stud rail at the bottom of the units (Stora Enso, 2016). Gavric et al. (2015b, 2015c), O'Ceallaigh & Harte (2019), Hughes (2020) and Rezvani et al. (2021) have identified standard angle brackets as the most suitable connector for wall-to-floor connections. Another option that has been considered suitable is the timber plate or stud rails at the bottom of the units which will be connected using self-tapping screws. These connections are advantageous because they allow flexibility in the location of ceiling and floor panels. Both of these connections will be further investigated experimentally as a part of the MODCONS project on C16-grade material. The wall-to-floor connections shall be subjected to a racking test carried out in accordance with EN 594 (CEN 2011). The racking frame at the University of Galway is shown in Figure 4.

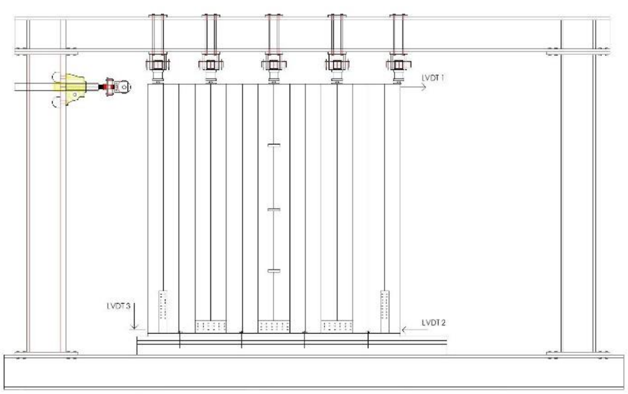

Figure 4: Racking frame.

The racking frame has the capability to apply a horizontal load of up to 200 kN and vertical point loads ranging from 1-5 kN. The displacements of the panel shall be monitored using linear variable differential transducers (LVDTs) at LVDT 1, LVDT 2 and LVDT 3 as shown in Figure 4. The deformations for the calculation of the horizontal racking displacement shall be taken as displacement at LVDT 1 minus the displacement at LVDT 2. The displacement at LVDT 3 which presents the vertical displacement or uplift of the panel is reported separately.

3. NUMERICAL MODELLING

3.1. Typical numerical models

In addition to experimental data and analytical models, numerical modelling of connections is a very important tool to obtain reliable results and understand the behaviour of connections. Finite element numerical analysis may be used as a predictive analysis approach for the experimental results. Izzi et al. (2018) proposed a numerical model to predict the mechanical behaviour and failure mechanisms of wall-to-floor connections assembled with angle brackets and hold-downs. The CLT panels and metal connectors have been modelled in ABAQUS as 3D solid bodies, whereas the nailed joints have been modelled as non-linear hysteretic springs based on Rinaldin et al. (2013). These models were analysed for shear, tension and combined shear and tension loads. Analyses were also carried out for various inclinations of the load between 0° and 90°. The results were then compared to the analytical models using Eurocode 5 (CEN 2005b). The results of monotonic analyses highlight the overestimation of the stiffness of the connection by the Eurocode 5 (CEN 2005b) model. The results for the cyclic analyses were an excellent match in terms of hysteretic behaviour and energy dissipation. The results of the bi-axial analyses exhibit a quadratic interaction relationship between shear and tension loads. Rinaldin et al. (2013) proposed a numerical model to estimate the dissipative capacity of connectors like hold-downs and angle brackets connecting the CLT wall panels to the foundation. The CLT walls have been modelled as elastic shell elements using ABAQUS. The connectors have been modelled as nonlinear hysteretic multi-spring elements and implemented as external subroutines. The results are then compared with experimental testing results. The proposed model was found to be quite robust and yielded a reliable estimation of the energy dissipated by the connectors.

Gavric et al. (2015) found that angle brackets are also capable of resisting tension loads in the addition to the shear loads they are intended to be used for. Rezvani et al. (2022) conducted a two-phase numerical analysis to study the effects of biaxial loading on wall-to-floor angle bracket connections. Phase I consisted of developing a 3D finite element model using ABAQUS and verifying with experimental data. Phase II involved using this verified model to analyse the performance of the connections under biaxial loading. ABAQUS has been used for finite element analysis and all parts of the connection, including the connector and screws have been 3D modelled. In comparison with experimental results, the numerical model showed high accuracy and was thus used for the evaluation of the behaviour of the connections under biaxial loading. The angle brackets experienced similar failure modes to monoaxial loading under lower loads. However, with the increase in load levels, the connections experienced different failure modes. D'Arenzo, Seim, et al. (2021) developed an innovative Titan V (TTV) angle bracket to achieve high performance in both the vertical-tensile direction and the horizontal-shear direction. D'Arenzo, Casagrande, et al. (2021) developed a finite element model using SAP2000 with an innovative microelement to model the TTV coupled shear-tension behaviour to take into account the nonlinear interaction between the vertical-tensile and horizontal-shear load. The model has been validated by comparing the results obtained from the nonlinear static analysis in SAP2000 with the experimental results and they were found to be in good agreement.

3.2. Numerical modelling of proposed connections

The proposed numerical model for the wall-to-floor connection as part of the MODCONS project shall be modelled using ABAQUS. The CLT wall manufactured from C16-grade material shall be modelled as a 3D solid element and meshed with C3D8R elements. The connections between CLT elements will not be modelled discretely but instead, the mechanical behaviour of the brackets will be defined within connector elements. The connector elements will be validated based on experimental results presented by O'Ceallaigh & Harte (2019) and then applied to larger proposed experimental racking tests on C16-grade CLT walls. The use of connector elements to define the behaviour of the angle brackets will allow for larger models of entire structures to be modelled in reduced computational time. A typical model of the proposed racking test on the C16-grade CLT wall is shown in Figure 5.

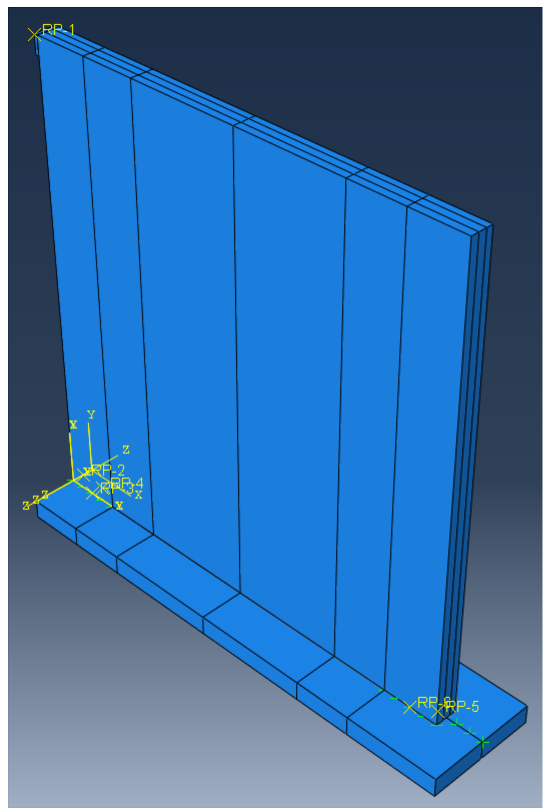

Figure 5: 3D numerical model of proposed connection in ABAQUS.

The CLT material properties shall be for C16-grade timber as per the studies carried out by O'Ceallaigh et al. (2018) and Sikora et al. (2016). Vertical and horizontal loads to replicate tension and shear loads shall be applied and the behaviour of the connections shall be studied.

4. CONCLUSIONS

This paper presents the ongoing work of the MODCONS Project focused on developing suitable and reliable connections details for CLT connections utilising C16-grade material. Angle brackets with self-tapping screws have been identified as the most feasible connection for the floor-to-wall connections for the modular units in the MODCONS project. Wall-to-floor connections using timber rails and self-tapping screws shall also be investigated. These connections will be tested under shear and tension loads to determine their behaviour for C16-grade CLT panels in addition to large-scale tests on CLT panels subjected to a racking test carried out in accordance with EN 594.

Numerical modelling of these connections will be carried out using ABAQUS and the finite element analysis results shall be validated using the experimental results. The numerical and experimental results will also be compared with analytical models using the provisions of Eurocode 5 (CEN 2005b). The combined analytical and numerical investigations will facilitate the design and detailing of a 7-storey modular mass timber building utilising C16-grade material.

5. ACKNOWLEDGMENTS

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