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DETERMINATION OF THE RACKING STRENGTH AND STIFFNESS OF CLT PANELS MANUFACTURED FROM C16-GRADE IRISH TIMBER

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ABSTRACT: This study examines the racking strength and stiffness of CLT panels manufactured from C16-grade timber using Irish Sitka spruce. The timber obtained from Sitka spruce in Ireland is typically graded as C16. In Europe, CLT is primarily manufactured with C24-grade timber, and most of the research available on the structural behaviour of CLT is presented for C24-grade material only. In this study, C16 grade material is examined by subjecting full-scale CLT panels manufactured using C16-grade CLT to racking resistance tests. The CLT wall panels are connected to CLT floor panels using only angle brackets and screws. A preliminary investigation has been conducted to verify the feasibility of a non-standard application of angle bracket connectors for the design of a multi-storey modular building using CLT made from C16-grade Irish timber.

KEYWORDS: Cross-laminated timber, CLT connections, C16-grade Irish timber, Racking resistance

1 – INTRODUCTION

Aligned with the recent shift in focus of the construction industry towards more sustainable construction materials, engineered wood products (EWPs) have gained prominence in the construction of medium to high-rise structures. One of the most popular EWP is cross-laminated timber (CLT), which is responsible for the rise in the construction of multi-storey timber buildings worldwide. CLT comprises at least three layers of parallel boards glued together using an adhesive under pressure and can rival traditional building materials like concrete and steel because of its light weight and high strength-to-weight ratio while being environmentally sustainable [1]. European CLT is primarily manufactured from C24-grade timber, and significant research and data are available on this grade of timber. However, there is an abundance of underutilised C16-grade timber which needs attention to increase its use in mass timber construction. The timber grown in Ireland, specifically Irish Sitka spruce timber, is primarily graded as C16 as per EN 338 [2]. In recent years, research has been carried out to establish the properties of Irish timber [3], [4], [5], [6], however, the use of C16-grade CLT in mass timber construction needs to be studied.

This study is part of ongoing research on modular CLT construction using Irish C16-grade CLT as a part of the Modular Mass Timber Building for the Circular Economy (MODCONS) project. The proposed modular building is seven stories high and has been designed as per Eurocode guidelines and Irish Building Regulations [7]. The modules are stacked in a balloon-framing arrangement and the connections are designed using commercially available connectors for expected load capacity, scalability and ease of deconstruction. Typical angle brackets with self-tapping screws have been used for wall-to-floor connections and have been tested under compression and shear loads [8]. The racking resistance of CLT walls is an important factor governing the structural performance of a mass timber building. A preliminary investigation has been carried out to determine the racking strength and stiffness of C16-grade

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CLT wall panels measuring 2.4 m in height and 1.2 m in length and connected to the floor panel using typical angle brackets and self-tapping screws. The CLT panels are subjected to racking loads as per EN 594 [9] and will inform the design of a multi-storey modular building constructed using C16-grade CLT [7].

2 – LITERATURE REVIEW

The most crucial part of a mass timber building system is its connections, and the connection design is governed by the Eurocode 5 [10] and European Technical Assessments (ETAs). Due to C24 being the most common grade used in mass timber construction across Europe, the guidelines provided by the Eurocode 5 [10] and ETAs are based on the experimental testing of C24-grade timber. The study of connections in mass timber building systems constructed using lower-grade timber is of particular interest to propel the rise in mass timber construction.

The most common wall-to-floor CLT connection is a combination of angle brackets and hold-downs. The shear load is resisted by the angle brackets, and the hold-downs are used to resist overturning. A number of full-scale CLT wall tests were performed as a part of the SOFIE project by Ceccotti et al. [11], [12], [13], where 2.95 m x 2.95 m wall panels were subjected to monotonic and cyclic loads to analyse their racking behaviour. The panels were designed to have a rigid behaviour, and angle brackets and hold-downs were used in the connections, which were designed to exhibit ductile behaviour. Subsequently, full-scale 3-storey and 7-storey buildings were tested, and ductile failure modes with fastener bending were observed. Dujic et al. [14] tested the racking behaviour of 2.44 m x 2.44 m wooden panels by subjecting them to monotonous and cyclic horizontal loads in combination with a constant vertical load. It was observed that the type of vertical load and the anchorage system greatly influenced the behaviour of the wall panels. Gavric et al. [15] investigated the cyclic behaviour of several configurations of single and coupled CLT wall panels by comparing the experimental results to the advanced analytical models developed for nonlinear pushover analysis of the CLT wall system. Different anchoring systems with varying types and number of fasteners were studied, and it was concluded that the design of the connection greatly influences the overall behaviour of the structural system. The number of fasteners in the vertical joints between the adjacent walls in a coupled wall system was observed to influence the kinematic behaviour of the CLT walls. This study was very important in establishing an analytical model to predict the behaviour of two-dimensional CLT wall systems. The CLT wall panel in the aforementioned studies was anchored to a steel foundation, which is typical for racking tests. D'Arenzo et al. [16] tested CLT walls anchored with shear-tension angle brackets, and the wall panels in this study were connected to the CLT floor panels. Hughes et al. [17] tested a CLT wall panel connected to a CLT floor panel using angle brackets and hold-downs to study the behaviour of tall CLT buildings under monotonic lateral loading and vertical loads replicating gravity loads at different storeys within a 10-storey CLT building. The vertical load was observed to have a significant influence on the behaviour of the wall system.

Since the overall behaviour of a CLT wall system was observed to be governed by the connection design, for the racking tests in this study, the CLT wall panel has been anchored to a CLT floor panel. The proposed modular building uses only angle brackets for wall-to-floor connections, unlike a traditional CLT wall-to-floor connection, which is a combination of angle brackets and hold-downs. Hence, in this preliminary study, a non-standard application of angle brackets has been investigated. The CLT wall panel is connected to the CLT floor panel using only angle brackets and self-tapping screws as they would be connected in a module and the preliminary racking tests are performed using this arrangement. The main objective of this study is to analyse and determine the behaviour of these connections in the context of C16-grade CLT and study their influence on the racking behaviour of a C16-grade CLT wall system.

3 – EXPERIMENTAL TESTING

The racking tests have been performed as per EN 594 [9] using the racking frame in the University of Galway as seen in Figure 1. This self-restraining racking frame has the capacity to apply a horizontal load of up to 200 kN. The vertical load is applied using a series of five actuators with loads ranging from 1 to 5 kN. The displacements have been monitored using linear variable differential transducers (LVDTs).

3.1 TEST MATERIALS

For the racking tests, CLT panels of two different thicknesses have been manufactured as per EN 16351 [18]. The 140 mm thick 5-layer (40-20-20-20-40) panels act as the floor panels, and the 120 mm thick 3-layer (40-40-40) panels act as the wall panels. Prior to manufacture, the C16 Sitka spruce boards are conditioned at a relative humidity of 65 ± 5% and

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a temperature of 20 ± 2°C. The boards are face-bonded using a one-component PUR adhesive with a spreading rate of 160 g/m^2 and subjected to a pressure of 0.6 N/mm^2 to form the panel. The wall panel is connected to the floor panel using Rothoblaas Titan F (TTF200) angle brackets in a fully fastened configuration using self-tapping LBS screws of 5 mm diameter and 50 mm length (LBS550).

3.2 TEST SETUP

Figure 1 shows the test setup used for the racking test. A 120 mm thick 3-layered CLT panel of 2.4 m height and 1.2 m width is connected to a 2.4 m x 1.2 m 5-layered panel, 140 mm thick. Two TTF200 angle brackets are connected at a spacing of 150 mm from each end and a 500 mm spacing between them. The connector spacings are calculated as per the guidelines of Eurocode 5 [10] and ETA-11/0030 [19] and are as shown in Figure 1.

The lateral or racking load is applied on the top of the leading edge of the panel via a contact roller connected to the frame, as shown in Figure 1. The five vertical actuators are equally spaced, allowing for 100 mm from the leading edge of the wall as per EN 594 [9]. The leading edge of the panel is the left edge, whereas the right edge of the panel shall be referred to as the trailing edge.

The displacements of the panel have been monitored using LVDTs at the locations indicated in Figure 1. LVDT 1 measures the lateral displacement at the top of the panel, and LVDT 2 measures the lateral displacement at the bottom of the panel. The lateral displacement or the racking displacement is calculated as the difference between the displacement at LVDT 1 and the displacement at LVDT 2. The displacement at LVDT 3 is the vertical displacement or uplift and is reported separately. Typically, in a racking test setup, the floor panel is fixed to the ground. However, the racking frame that was used for the tests does not have this provision. Hence, a 2.4 m x 1.2 m base frame made using hollow rectangular sections was fixed onto the base of the racking frame. The floor panel was then fixed to this base frame. Therefore, LVDTs have been installed to measure the displacements of the floor panel and frame relative to the ground to quantify this contribution to the wall displacement. LVDT 4 measures the uplift of the floor panel relative to the ground, and LVDT 5 measures the uplift of the base frame relative to the ground. LVDT 6 measures the lateral movement of the floor panel relative to the ground. LVDT 7 measures the lateral deformation of the racking frame. The readings from LVDT 4, LVDT 5, LVDT 6 and LVDT 7 shall be used to correct the uplift and racking displacement of the panel.

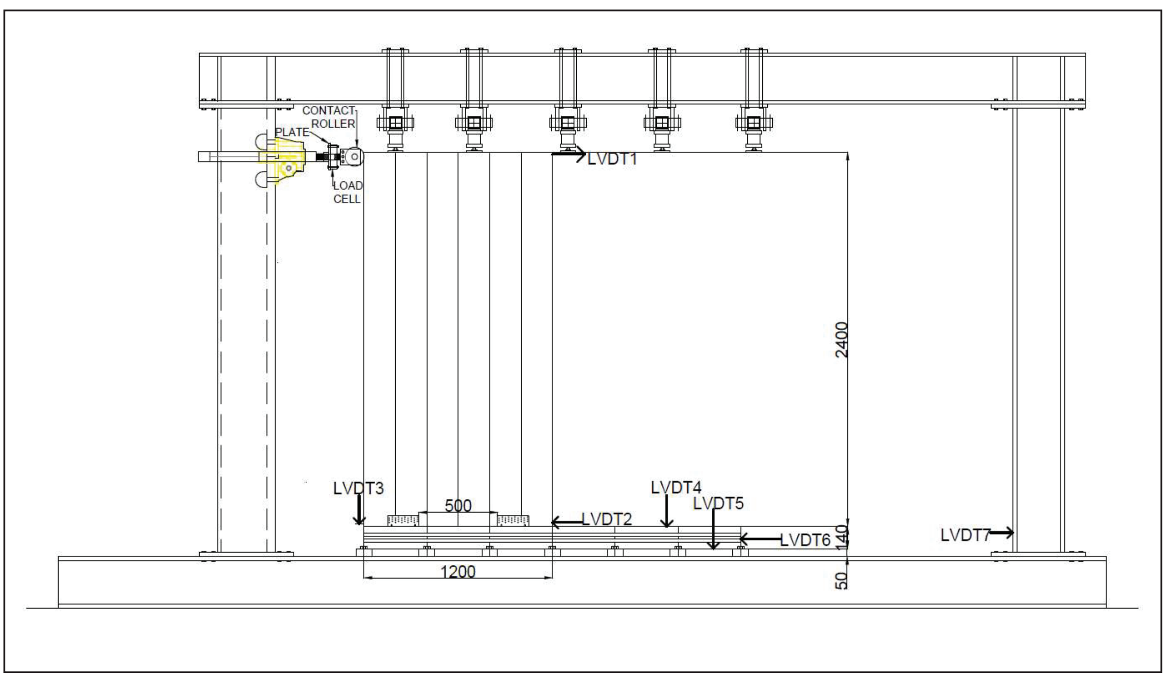

Figure 1: Racking test layout of 2.4 m x 1.2 m CLT panel

3.2 LOADING PROTOCOL

The loading procedure for the racking test is in accordance with the procedure outlined in EN 594 [9]. Racking loads (F) shall be applied with and without vertical loads (F_v). The first cycle before the strength test is the stabilising load cycle, where a vertical load of 1 kN (F_v = 1 kN) shall be applied to the head binder and maintained for a period of 120 seconds. The load shall then be removed, and the panel shall be allowed a recovery period of (600 ± 300) seconds before continuing the test. That concludes the stabilising cycle, and subsequently, the strength test is performed. After applying the appropriate vertical loads, the horizontal racking load is applied at an appropriate rate to ensure that 90 % of the maximum racking load (F_{max}) is reached within (300 ± 120) seconds. Once the maximum racking load (F_{max}) is reached, the wall system is maintained at this load for approximately 120 seconds. The lateral load is then gradually decreased, and after the lateral load is removed, the vertical load is gradually removed until there is no external load on the wall system. Once all the load is removed, the wall system is allowed to rest for approximately 300 seconds before commencing the subsequent cycle.

The racking displacement of the panel is calculated as shown in Eq. (1).

$$v = v_{LVDT1} - v_{LVDT2} \tag{1}$$

Where v_{LVDT1} is the lateral displacement at LVDT 1 and v_{LVDT2} is the lateral displacement at LVDT 2 (Figure 1).

The racking strength of the panel is the maximum load attained during the test as shown in Eq. (2).

$$F = F_{max} \tag{2}$$

The racking stiffness is calculated as shown in Eq. (3).

$$R = \frac{F_{40} - F_{10}}{v_{40} - v_{10}} \tag{3}$$

Where F_{10} and F_{40} are the loads corresponding to 10% and 40% of F_{max}, and v_{10} and v_{40} are the displacements corresponding to 10% and 40% of F_{max}, respectively. Therefore, the racking stiffness (R) is the slope of the line between 10% and 40% of the maximum racking load (F_{max}).

4 – ANALYTICAL MODEL

Gavric et al. [15] developed an analytical model to predict the total lateral displacement (δ_{tot}) of a wall system when a lateral load is applied, which is a sum of the displacements due to the four deformation mechanisms: rocking (δ_r), sliding (δ_{sl}), shear (δ_{sh}) and bending (δ_b) as shown in Eq. (4).

$$\delta_{tot} = \delta_r + \delta_{sl} + \delta_{sh} + \delta_b \tag{4}$$

Rocking and sliding were found to be the most important deformation components, and based on that, Gavric et al. [20] proposed three possible cases of predominant behaviour, namely, rocking behaviour, combined rocking-sliding behaviour, and sliding behaviour. The equations formulated by Gavric et al. [15] for these deformation behaviours have been used to calculate the deformations of the wall system presented in this study.

The results from the experimental testing undertaken by [15] demonstrated that angle bracket connections have notable strength and stiffness in tension, in addition to shear, and the same has been assumed for this study. The stiffnesses of the TTF200 angle bracket connections in tension and shear have been taken from the results of the monotonic tests on the small-scale connections [8] and have been tabulated in Table 1.

Table 1: Elastic stiffness values of TTF200 from the small-scale tests

Load	**Elastic stiffness k_{el} (kN/mm)**
Compression	9.20
Shear	10.55

A schematic diagram of a CLT wall panel subjected to horizontal loads is shown in Figure 2. Using the force-displacement relationship $F = ku$, the expected force and displacement for each of the connectors are calculated. The displacements u_1 and u_2 can be considered as factors of the distance from the centre of the connector to the lower corner of the wall (point B in Figure 2), x_1 and x_2, and the angle of rotation φ as shown in Eq. (5) and Eq. (6).

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$$F_1 = k_{el}u_1 = k_{el}(x_1\varphi) \tag{5}$$

$$F_2 = k_{el}u_2 = k_{el}(x_2\varphi) \tag{6}$$

The angle of rotation φ is derived by solving the moment equilibrium about point B as per Eq. (7) and substituting Eq. (5) and Eq. (6) in Eq. (7).

$$Hh = F_1x_1 + F_2x_2 \tag{7}$$

The value of H is the lateral load applied on the panel, and h is the height of the panel. The value of k_{el} for compression from Table 1 is used in the calculation. The values of x_1 and x_2 from the experimental setup (Figure 1) are 950 mm and 250 mm, respectively. The value of the angle of rotation φ is used to calculate the values of u_1 and F_1 from Eq. (5) and u_2 and F_2 from Eq. (6). The expected values of u_1 and u_2 calculated are then compared to the values of u_1 and u_2 obtained from the experimental results.

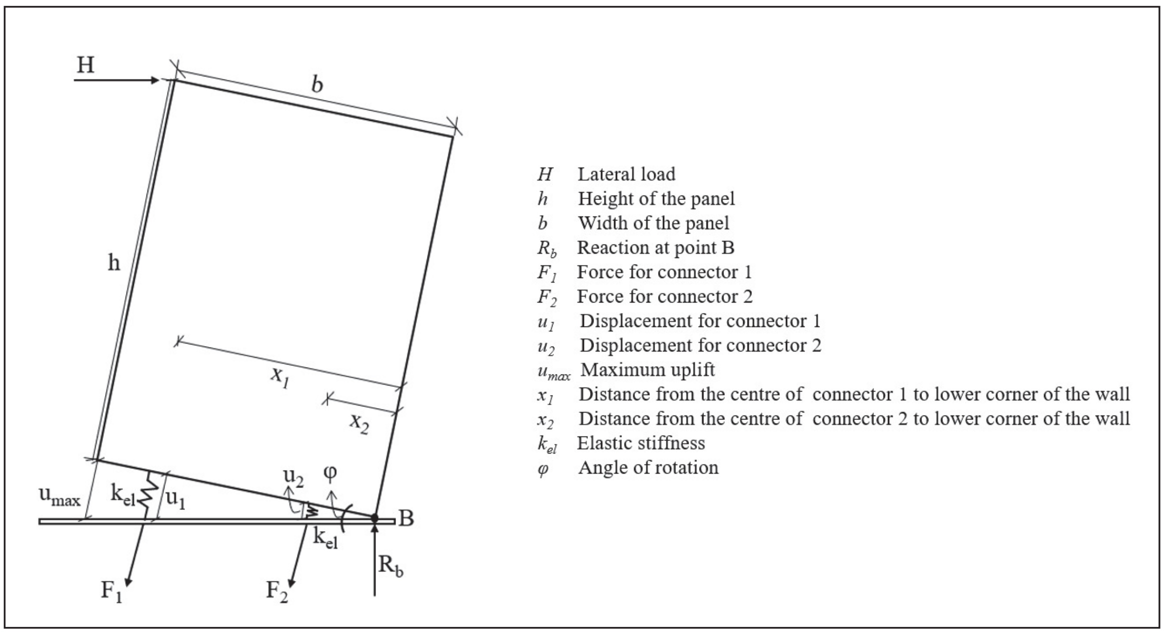

Figure 2: Schematic diagram of a CLT wall subjected to lateral loads

5 – RESULTS AND DISCUSSION

For the preliminary test discussed in this paper, the racking test was carried out with no vertical loads. The main objective of this test was to gauge the feasibility of the non-standard application of the angle bracket connections in the modular building without hold-downs. The racking load was applied in three cycles, such that the connections behaved elastically. The lateral displacement of the wall system is given by the difference between the displacements recorded by LVDT 1 and LVDT 2. The vertical displacement is given by the uplift recorded by LVDT 3. The displacements recorded by LVDT 4, LVDT 5, LVDT 6 and LVDT 7 were negligible and hence have been ignored. This means that the floor panel demonstrated rigid behaviour as if it were directly connected to the floor of the laboratory.

The load-displacement curves obtained from the experimental testing are presented in Figure 3. The values of maximum racking displacement (v_{max}), maximum racking force (F_{max}), racking stiffness (R) and maximum uplift (u_{max}) are tabulated in Table 2.

Table 2: Values obtained from the racking test

Parameter	Value	Unit
Maximum racking displacement (v_{max})	9.42	mm
Maximum racking force (F_{max})	5650.55	N
Racking stiffness (R)	611.07	N/mm
Maximum uplift (u_{max})	4.30	mm

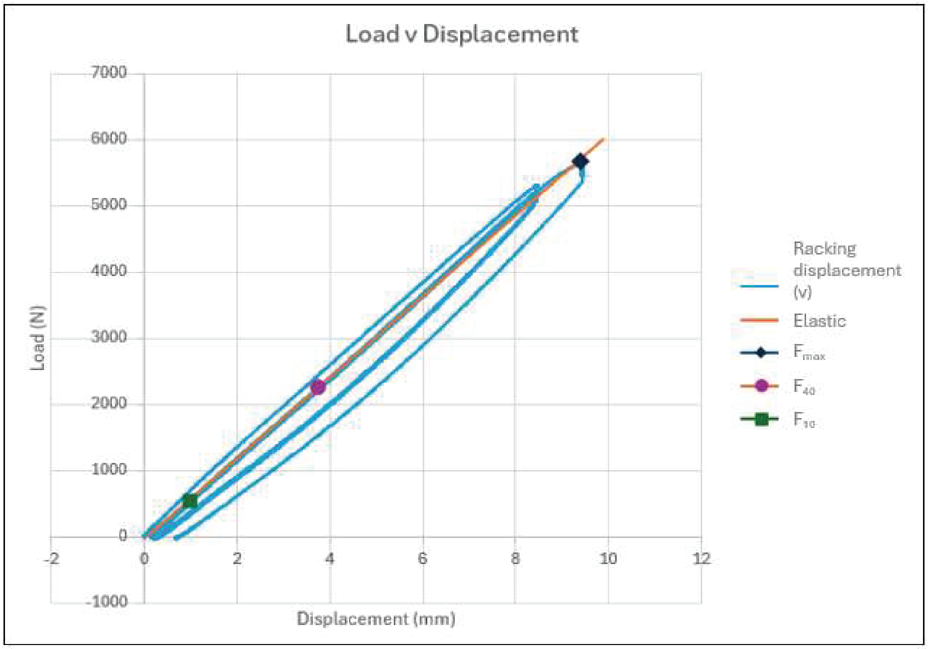

Figure 3: Load-displacement curve obtained from the racking test

For the maximum racking force (F_{max}) obtained from the experimental testing, the expected values of displacement for the connectors are calculated using Eq. (5), (6) and (7). The displacement values of the connectors have also been extrapolated for the experimental testing using the value of the maximum uplift (u_{max}) obtained from the test. These values are presented in Table 3.

Table 3: Analytical and experimental values of displacement (u) for the connectors

Connector	Analytical displacement (mm)	Experimental displacement (mm)
Connector 1 (u_1)	1.45	3.40
Connector 2 (u_2)	0.38	0.89

The analytical force values (F_1, F_2) for each of the connectors are calculated using the corresponding displacement values (u_1, u_2) using Eq. (5) and (6) and the elastic stiffness value for this calculation is taken as the elastic stiffness obtained from the small-scale compression tests from Table 1 due to the loading configuration of these tests. These values are compared to the characteristic yield values obtained from the small-scale compression tests [8] and the characteristic load-carrying capacity of the connectors reported in Rothoblaas technical documentation, which has been calculated using ETA-11/0496[21]. The values from Rothoblaas are reported for C24-grade timber and have been adjusted for C16-grade timber. The force values are presented in Table 4. The values of forces in the connectors (f_1, f_2) are also calculated using the moment equilibrium equations and are listed in Table 4.

Table 4: Comparison of the force values for the connectors

Source	Force (kN)
Analytical model, Connector 1 (F_1)	13.34
Analytical model, Connector 2 (F_2)	3.50
Moment equilibrium, Connector 1 (f_1)	11.3
Moment equilibrium, Connector 1 (f_2)	11.3
Characteristic yield from small-scale tests (F_{yield})	22.42
Characteristic load-carrying capacity from Rothoblaas (F_R)	11.06

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(Table 3). The force values obtained from the analytical calculation values (Table 4) are considerably less than the characteristic yield value evaluated from the small-scale compression tests. The force in the connectors from the moment equilibrium equation is almost equal to the value of the characteristic load-carrying capacity (F_R) provided by the Rothoblaas documentation, adjusted for C16-grade timber, which suggests that the connector 1 is almost at capacity for the given lateral load. However, the force for connector 1, F_1, is greater than F_R, suggesting potential plasticity in connector 1. This finding indicates that although angle bracket connections exhibit a considerable amount of stiffness in small-scale compression tests, they do not provide significant racking stiffness on their own in wall systems. This implies that connectors designed specifically for strength and stiffness in tension are necessary to assess the racking strength and stiffness of the CLT wall system.

6 – SCOPE OF FUTURE WORK

The results of this preliminary investigation show that even though the non-standard application of the angle brackets may be reasonable in the context of a modular building, it is not feasible to test a CLT wall system without hold-downs. The modular building shall also consist of plate connectors, which are used for module-to-module connections. The module-to-module connection also creates a shear diaphragm which can resist lateral loads. Hence, the plates for the module-to-module connections shall also be studied for racking loads.

This paper focuses on the study of the racking behaviour of single-panel walls. However, the coupled wall behaviour also needs to be studied as expected in an actual mass timber building system. The next phase of this study shall focus on the coupled wall behaviour of CLT panels subjected to racking loads. This will comprise two 2.4 m x 1.2 m CLT wall panels connected together with Rothoblaas SLOT connectors, which are an alternative to traditional connections like half-lap joints or spline joints. Similar to the current test, the wall panels will be connected to the floor panels using angle brackets, hold-downs and self-tapping screws. Racking loads and vertical loads shall be applied, and the panels shall be tested under the provisions of EN 594 [9].

After the experimental testing is complete for both single-wall behaviour and coupled-wall behaviour, finite element numerical models shall be prepared using ABAQUS. The material properties of C16-grade timber from the works of Sikora et al. [4] and O'Ceallaigh et al. [5] shall be used for modelling the CLT panels. The connections shall be modelled based on the work of Izzi et al. [22] and D'Arenzo et al. [23]. Horizontal and vertical loads shall be applied to mimic the loads in the experimental testing. The numerical models shall be validated using the experimental results. The results of these numerical analyses shall inform the parametric study of the behaviour of connections in a mass timber building using C16-grade CLT.

7 – CONCLUSION

The racking strength and stiffness of a CLT wall system manufactured from C16-grade timber have been investigated. A 2.4 m x 1.2 m wall panel of thickness 120 mm has been connected to a 2.4 m x 1.2 m floor panel of 140 mm using two TTF200 angle brackets and LBS550 screws in a fully fastened configuration. The racking test was performed as per EN 594 [9], with no vertical loads. This preliminary test was carried out to verify if the capacity of a non-standard application of angle brackets without hold-downs when determining the racking strength and stiffness of a C16-grade CLT wall system. Linear variable differential transducers (LVDTs) were used in different positions to measure the racking displacement and uplift.

Load-displacement curves were plotted for the racking loads applied and the displacements measured by the LVDTs. The maximum racking displacement (v_{max}), maximum uplift (u_{max}), maximum racking force (F_{max}) and racking stiffness (R) are obtained from the experimental load-displacement curves. Using the analytical model formulated by Gavric et al. [15], the expected displacement values for the connectors (u_1, u_2) are calculated for the experimental maximum racking force (F_{max}), which are compared to the displacement values extrapolated from the experimental results. The analytical model predicts lower displacement values for the same lateral loads. The expected force values (F_1, F_2) are also compared to the characteristic yield values (F_{yield}) obtained from the small-scale tests and the characteristic load-carrying capacity (F_R) provided by the Rothoblaas documentation, adjusted for C16-grade timber. The F_1 value was greater than the F_R value, which suggests potential development of plasticity in connector 1, but the F_1 and F_2 values were lower than the F_{yield} value, which suggests no yielding of the connectors has occurred. This implies that while a connection using a non-standard application of angle brackets is possible in the context of a wall-to-floor connection for a modular building, hold-downs are necessary for the racking tests of a wall system.

After this preliminary study, racking tests of C16-grade CLT wall systems shall be performed using hold-downs in addition to the angle brackets. Additionally, the performance of plate connectors used for module-to-module connections shall also be studied. Subsequently, the coupled wall behaviour of C16 CLT walls connected using Rothoblaas slot connectors shall also be studied. Finally, finite element models of these racking tests shall be developed and analysed using ABAQUS. These numerical models shall inform the development of a finite element model of a C16 CLT module, which will form the basis of a parametric study of the proposed CLT modular building using C16-grade Irish timber.

8 – ACKNOWLEDGEMENT

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