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EXPERIMENTAL STUDY OF A TYPICAL EXTERNAL WALL-FLOOR-WALL CONNECTION IN A CLT PLATFORM TYPE CONSTRUCTION

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ABSTRACT: This paper presents experimental studies of a typical external wall-to-floor-to-wall connection in a cross laminated timber (CLT) platform type construction in context of disproportionate collapse resistance. The studied connection mimics the finite element models developed by other authors in the international timber robustness research community. The assembled specimens were tested with aim of staying in the linear elastic range and understand how the rate of loading affects CLT and its connections. This study presents data of the observed behaviour of CLT, steel brackets and screws subjected to different rates of loading. Obtained results and observations will inform future testing programmes and experimental analyses whereby aim is to test the specimens beyond the linear elastic range and to failure.

KEYWORDS: CLT buildings, disproportionate collapse, experimental analyses, rate of loading, wall-to-floor-to-wall

1 INTRODUCTION

Cross laminated timber (CLT) is a relatively new construction material and both CLT balloon type and platform type [1, 2] construction methods have been increasingly popular in the building industry in the past three decades to build multi-storey buildings.

Some of the reasons are the advantages of using CLT over traditional materials such as concrete, steel and even timber used in timber frame construction method. For example, CLT panels of various sizes are manufactured and cut with high accuracy off-site in a factory. Assembly of CLT structure on site is usually shorter compared with building with concrete and/or steel, depending on the project size and complexity, requiring less person hours and produces less waste [3]. CLT structures could be lighter than steel and are lighter than equivalent concrete structures thus require less concrete for foundation. CLT has high strength to weight ratio compared to steel, concrete and masonry. In addition, CLT offers good quality and healthy living spaces and has a pleasant feel, should it be exposed inside of a building.

Many schools, hospitals and other commercial buildings have been built with CLT. Furthermore, the shortage in residential sector still exist and a portion of residential buildings could be built with the CLT. The United Nations (UN) projections are that quite a significant number of residential units will be required in the near future, a 2.3 billion new urban dwellers by 2050 – and entail the production of an enormous volume of housing and infrastructure [4].

Along with many other already available and newly emerging engineering solutions, using CLT to build some of the buildings could contribute to a more sustainable construction industry and to reaching the net zero commitment.

As any other building and structure, multi-storey buildings designed as a CLT platform type construction ought to be sufficiently robust to overcome any loads which may result in disproportionate collapse.

Experimental study presented in this paper considered the external wall-to-floor-to-wall (WFW) CLT connection which can be found in a multi-storey platform type building. Widely used construction practices for connecting CLT WFW were researched and a typical connection detail with a single bracket and floor-to-wall screw system was used to assemble the testing specimens.

The effect of different rates of loading (ROL) on the WFW connection and stiffness in the linear elastic range were studied which should inform future testing whereby specimens will be tested beyond linear elastic range including until failure.

Design for disproportionate collapse resistance requires consideration of stiffness and rotational capacity of structure's details, such as vertical and horizontal element connections and fixings. Sufficient tie forces should be present to develop catenary action in beams and membrane action in floors when an alternative load path is being developed at the time of sudden loss of a key structural element. Should stiffness be too high the catenary and/or membrane action cannot develop.

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2 LITERATURE REVIEW

Current UK based legislation, codes and guidelines account for disproportionate collapse resistance in a prescriptive manner by relying on expertise acquired through previous research and construction practices mainly based on concrete and steel structures.

The UK Building Regulations have changed since Ronan Point disproportionate and progressive collapse incident occurred in 1968, whereby now the Approved Document, Part A defines disproportionate collapse as: "The building shall be constructed so that in the event of an accident the building will not suffer collapse to an extent disproportionate to the cause." [5]. It is worth noting that disproportionate collapse can lead to progressive collapse and progressive collapse can be disproportionate.

Design codes reference the term robustness which shall account for design to resist disproportionate collapse [6]. For the case of mid-rise timber structures, design to avoid disproportionate collapse is often left solely to engineering judgement [7] although guidance such as Practical guide to structural robustness and disproportionate collapse in buildings is available [8]. One strategy is that each element of a structure shall develop a resistance mechanism – an alternative load path to ensure sufficient robustness against accidental loading cases applied to a structure in the design process.

A thorough review of international research on structural robustness and disproportionate collapse up to 2011 has been undertaken by Arup and published by the UK's Department for communities and local government [9]. It can be highlighted that limitations such as lack of guidance on CLT and behaviour of walls with openings are identified. These can be attributed to lack of disproportionate collapse resistance and robustness of CLT specific research at the time. Nevertheless, Recommendation 19 proposes to undertake a review of the robustness of timber construction and connection including research is urgently undertaken to investigate methods by which effective horizontal tying can be achieved in timber.

Byfield et al. [10] review of progressive collapse research and regulations highlighted guidelines, procedures and methods which are mostly grounded in concrete and steel. Nevertheless, Byfield et al.'s [10] comment that despite tying force method is easiest to implement, it does not require additional structural analysis. Furthermore, constraint of the alternative load path method is being underlined whereby requirement that only one key element at a time is to be removed to check the ability of the structure to redistribute loads without leading to a disproportionate collapse.

Experimental testing to mimic key element removal is related to rate of loading and load removal. Gerhards' [11] study reports observations from a large number and broad range of timber products subjected to different load durations and rates of loading. Gerhards concluded that both do affect timber products. ROL affects ultimate stresses namely tension and compression perpendicular to the grain. Furthermore, further research is suggested too.

More recent reviews of timber robustness were undertaken by Huber et al. [12], Voulpiotis et al. [13] and Cost Action FP1004 [14]. Currently active are CA20139 [15] and CEN/TC250 N3288 [16]. Latest research for example by Bita et al. [7,17], Huber et al. [18, 19], Przystup et al. [20] offers insights to their vast experimental studies for mostly floor-to-floor CLT connections to better understand development of catenary action and horizontal tie forces. These studies are also complemented with numerical finite element modelling.

Akter et al. [2] and Huber et al. [18, 19] study WFW CLT connection in a platform type construction. They undertook multiparametric finite elements analyses of numerical models exploring joint stiffness and Akter et al. [2] studied the impact of wall height, floor length and wall and floor thickness on joint stiffness. Their model predicted a stronger influence of the wall thickness over the floor thickness on the floor connection's rotational stiffness [2]. It is worth noting that floor to wall connection is usually modelled with conservative assumption that the rotational stiffness is negligible due to hinged connection in structural model and calculation [2].

Bruehl et al. [21] studied moment-rotation behaviour in a semi-rigid GL24h timber doweled joint and its ductility to determine the joint stiffness. Evidently the main principle is that should joint be too stiff without any rotational capacity then the timber element would fail in a brittle manner next to the joint without any benefit.

Furthermore, insurance specialists in the UK are currently preparing a framework document which should result in reviewing models to progress and account for new materials and construction methods, such as CLT. Therefore, understanding the risks and mitigation measures when using CLT is important and would support assessing the relevant insurance metrics so that the premiums would be commensurate with risks and therefore making CLT structures more feasible to insure for all involved stakeholders [22].

Authors are not aware of a CLT specific report that would highlight failure of CLT identifying disproportionate collapse and investigation of root causes. Nevertheless, failure of balcony due to moisture was highlighted in oral presentation by the author Nocetti [23] at Rothoschool event in London in 2019.

More timber expertise generally and CLT specifically is required, through research and experimental analyses. These should include studying different typologies and connections between structural timber elements. Inherent material properties of timber prevent formation of plastic hinges hence indicate brittle failure. Research of dynamic response to adverse loading, rate of load within instantaneous load duration capturing joint's stiffness and its ability to plastically deform is required. This research responds to calls by the international robustness community for more experimental studies [2, 10, 11, 13].

3 THE EXPERIMENTAL PROGRAMME

Rate of loading (ROL) within instantaneous load duration on CLT is relatively unknown variable and this is an exploratory study to understand better the impact of changing ROL to inform future testing of the WFW connection. Furthermore, consideration to observe any available rotational stiffness and how it is affected by the ROL in the considered WFW CLT connection.

A series of non-destructive experiments have been performed with intention to stay inside the linear elastic range. Specimen arrangement was focused on the WFW connection level and considered the effect of ROL on the WFW setup at the WFW connection level arrangement. A typical multi-storey platform type CLT building, which would be a class 2B was considered in this study [5, 8]. Three approaches are suggested as levels of robustness commensurate with routine risks, i.e. provision of vertical and horizontal ties, alternative load path(s) to be available upon removal of elements, which is adopted for disproportionate collapse resistance, and specific load resistance method (the provision of key elements) [8].

This paper highlights experimental programme of a WFW connection adopting testing methodologies previously prepared and used as comparison whilst developing finite element modelling. The latter were developed by Akter et al. [2], Huber et al. [10] and Bita et al. [11, 13].

Furthermore, this experimental programme is part of a wider research programme which will study disproportionate collapse resistance of CLT buildings at connection and system level.

3.1 TESTING SET UP ARRANGEMENT

The testing arrangement in this research programme as shown in Figure 1 comprises vertical metal block (1) holding the hydraulic actuators (2 and 3), the horizontal metal blocks (1T and 1B) and metal brackets (4T and 4B).

The hydraulic actuator (2) was connected to a manually operated hydraulic single-acting cylinder-pump and a stop valve (not shown in the drawing).

The hydraulic actuator (3) used in testing had a 25 kN load capacity and piston rod with 260 mm (+/-130 mm) stroke length capabilities.

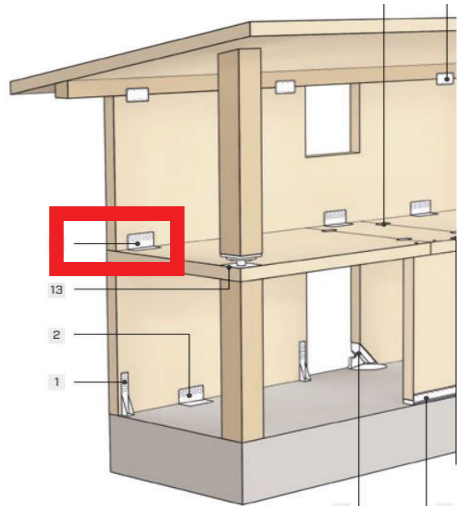
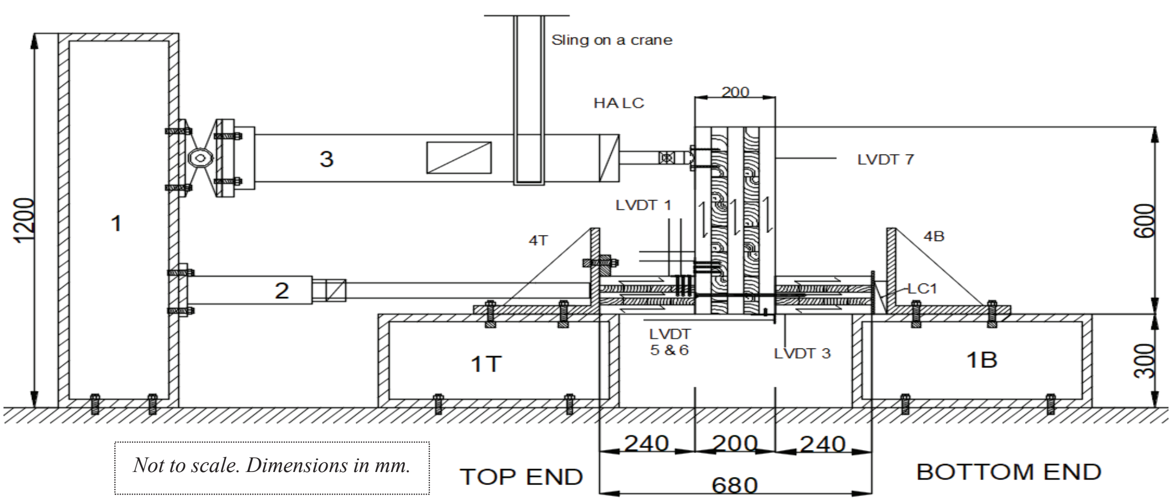


Figure 2: *The WFW connection addressed in the testing [24]*

The testing set up was arranged to mimic a cut at connection as shown in Figure 2, comprising ground floor wall, first floor panel and the first floor wall. Similar experimental arrangement was used elsewhere [2, 18].

The hydraulic actuator (3) was articulated at its rear. At its front a ball-and-cup arrangement was created. The ball part is attached at the end of the load cell which is screwed at the tip of the actuator's piston rod. The ball part is aligned and positioned at the centre of the cup part, which is attached to the floor element of the CLT specimen allowing the hydraulic actuator's piston rod to progress horizontally and upwards when the CLT floor element starts to rotate when subjected to the applied load.

Instrumentation used in this experimental programme were Linear Variable Displacement Transducers (LVDTs) and load cells (LCs) to detect displacements and loads as displayed in Figure 1.



Not to scale. Dimensions in mm.

Figure 1: *Near side (NS) cross-section of the testing set up*

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3.2 MATERIALS AND TESTING SPECIMENS

Materials used in testing were a combination of widely available commercial products and also generic products to consider their behaviour beyond a single manufacturer.

Self-tapping screws were obtained by Reisser and Spax, mechanical fixings (brackets) and fasteners (screws) were supplied by Rothoblaas and CLT was supplied by StoraEnso, both industry partners to this research.

Generic product, angle brackets made of mild steel were produced at University of Bristol. Rothoblaas brackets are made of zinc plated carbon steel. Rothoblaas screws are made of galvanized carbon steel and fully threaded [24]. Reisser screws are made of carbon steel rod according to EN10268 [25] and are fully threaded. Spax screws are made of carbon steel and are partially threaded [26, 27]. Dimensions are tabulated in Table 1.

Table 1: *List of material variables used in the testing, where A indicates type of timber, B type of bracket, WS wall screw and FWS floor-to-wall screw*

Item	Description
A1	CLT 5ply floor, 200 mm thick
A2	CLT 5ply wall, 120 mm thick
B1	Generic, 200x60x60x2 mm thick
B2	Rothoblaas, Nino15080, 2.5mm thick
WS1	Reisser, R2 Pan, 5.0x60 mm
WS2	Rothoblaas, LBS560, 5.0x60 mm
FWS1	Spax, wirox, 6.0x280 mm
FWS2	Rothoblaas, HBS6280, 6.0x280 mm

The specimens were assembled in combination of either:

UoB = 1x A1 + 2x A2 + 1x B1 + 60x WS1 + 1x FWS1
or
RO = 1x A1 + 2x A2 + 1x B2 + 36x WS2 + 1x FWS2

Where UoB means specimen with generic bracket (B1) and RO means specimen with Rothoblaas bracket (B2).

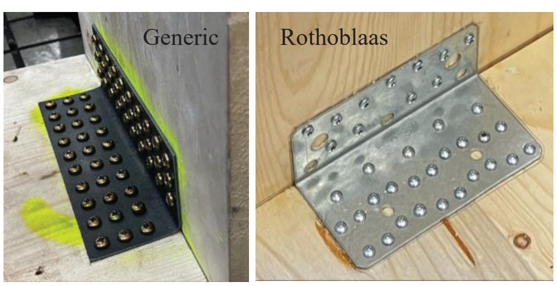

Figure 3: *Generic and Rothoblaas bracket used in testing (figures are not to scale)*

CLT was supplied and delivered cut-to-measure, then assembled in the laboratory to widely accepted and currently used CLT construction practice as per manufacturer's recommendations and as referenced in Swedish Wood CLT Handbook [24-28]. CLT elements and assembled specimens were kept dry at all times.

The humidity and temperature of the air in the large storage space was monitored over several weeks. Average temperature being 21.0°C and relative humidity 37.41%. The moisture content of the CLT was measured with a handheld moisture meter.

Testing specimen arrangement at connection level as shown in Figure 3 shows a typical connection in a multi-storey platform type CLT building. It comprises two wall elements and one floor element, each made of a C24, 5-ply CLT panel, connected with mechanical fixings tabulated in Table 1.

The floor and the bottom wall are fixed with a floor-to-wall screw while the top wall and the floor are connected with an angle bracket which is fixed with a number of self-tapping screws to both the top wall and the floor element.

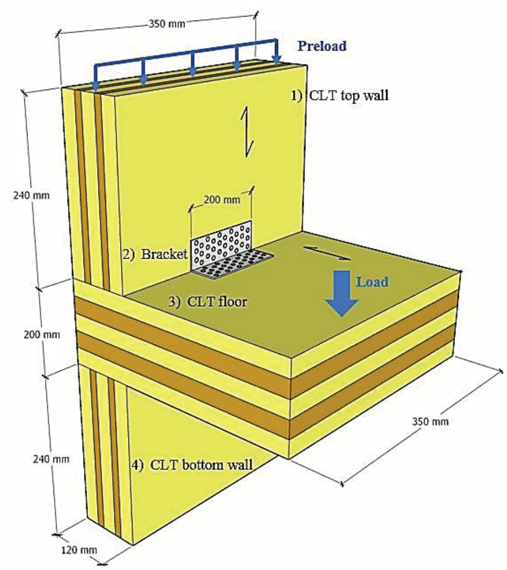

Figure 4: *Schematic of WFW testing specimen (not to scale)*

3.3 TESTING REGIME

Testing programme commenced with numerous preliminary trials to verify appropriateness and workability of the testing set up arrangement and instrumentation set up.

As supply of the CLT was limited, it was appropriate for the preliminary trials to be conducted using timber frame like specimens composed of C24 timber studs and oriented strand board (OSB) panels, fixed with self-tapping screws.

Following the preliminary trials the main experiments were performed with CLT specimens as displayed in Figure 5.

They were placed on the horizontal metal blocks in-between the metal brackets and preloaded with gravity loads of 18 kN induced by the hydraulic actuator (2).

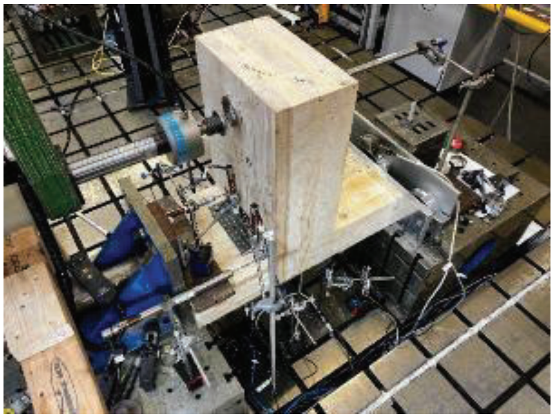

Figure 5: *Example of CLT specimen and the testing set up*

Gravity loads were combined as an accidental loading combination, based on an 8-storey CLT residential building with 6 m spans and 1.5 kN/m^2 live loading as per [29].

Then the metal brackets were bolted and fixed to hold the specimen in position which was restrained and rigidly fixed to mimic real conditions of fixing.

The hydraulic actuator loading operation comprised hold stage, load stage and load release stage.

The load from the hydraulic actuator was applied to the floor element at a predefined rate as tabulated in Table 2, to understand the impact of the ROL application.

ROL was one variable considered in this set of experiments. The load was removed immediately after reaching the predefined displacement.

Table 2: *Loading cases used in the testing, where C indicates the rate of loading (ROL)*

Item	Loading case	Abbreviation
C1	ROL = 6 mm/min	ROL6
C2	ROL = 600 mm/min	ROL600
C3	ROL = 3,600 mm/min	ROL3.6k
C4	ROL = 6,000 mm/min	ROL6k

C1 represents quasi-static load while C2, C3 and C4 represent an accidental loading to account for a scenario of disproportionate collapse modelled by a removal of a key element. In this testing this would be an internal wall in the ground floor.

Displacement controlled loading was used in all loading cases. Data collection frequency when using load scenario C1 and C2 was 1 kHz while using load scenario C3 and C4 it was set to 5 kHz.

4 RESULTS AND OBSERVATIONS

4.1 RESULTS

The results and observations of experiments are presented with series of graphs and tables below. Results obtained at C4 are not representative since they appear to be beyond the linear elastic state yet are still presented. The studied WFW connection is identified as a semi-rigid connection.

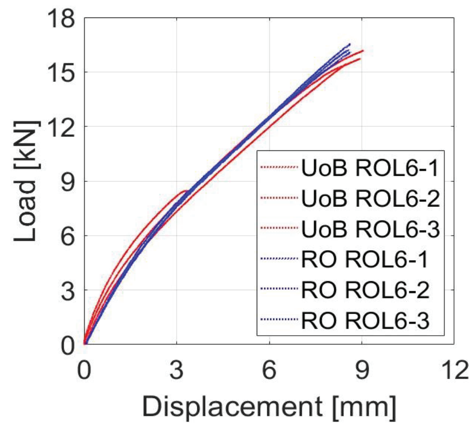

Figure 6: *Load – displacement for ROL 6 mm/min*

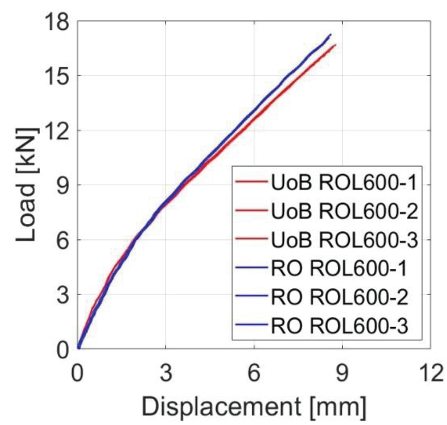

Figure 7: *Load – displacement for ROL 600 mm/min*

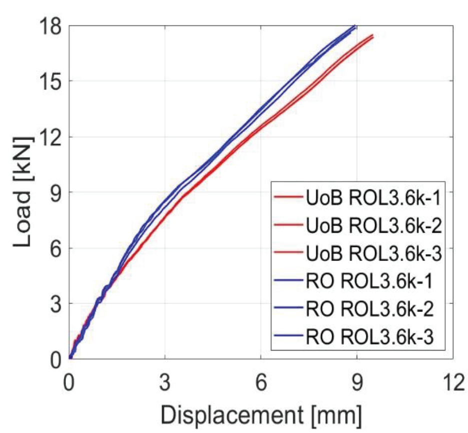

Figure 8: *Load – displacement for ROL 3,600 mm/min*

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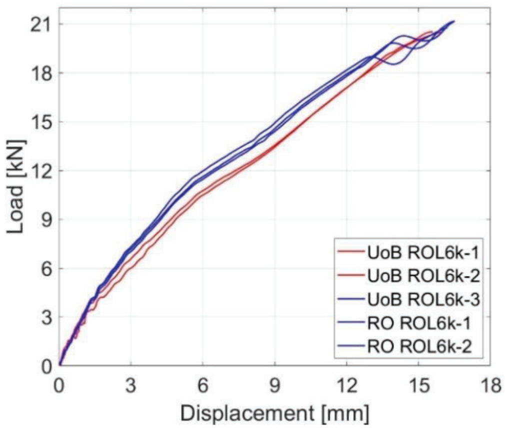

Figure 9: *Load – displacement for ROL 6,000 mm/min*

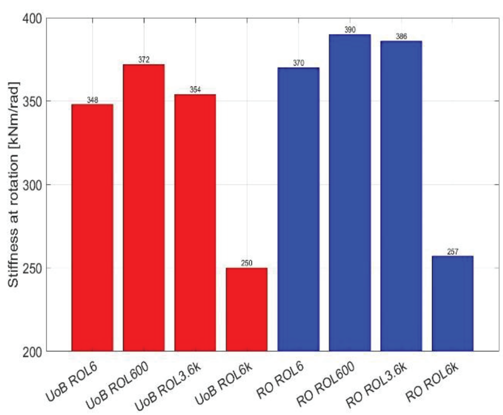

Figure 10: *Stiffnesses at rotation for rates of loads C1-C4*

Stiffness at rotation is calculated using engineering mechanics equations.

$$M = F \times L \tag{1}$$

$$\varphi = tan^{-1}(\frac{u}{L}) \tag{2}$$

$$K = (\frac{M}{\varphi}) \tag{3}$$

Where,

M = moment [kNm], F = force [kN], L = length from point of loading to wall is constant 440 mm (0.44 m),
u = displacement of app. 9 mm (0.09 m) for C1-C3 and app.16 mm (0.016 m) for ROL C4,
φ = rotation and is constant 0.02 rad and 0.036 rad,
K = rotational stiffness [kNm/rad].

Table 3 below tabulates the stiffness values for at the achieved rotations. Moreover, there is certain stiffness available in contrast to analytical approach of having hinged floor-to-wall joint where rotation is not considered.

Table 3: *Stiffness values for tests with generic bracket B1 UoB*

ROL	F	M	K
UoB ROL6	15.809	6.956	348
UoB ROL600	16.519	7.268	372
UoB ROL3.6k	17.431	7.670	354
UoB ROL6k	20.487	9.014	242

Table 4: *Stiffness values for tests with Rothoblaas bracket B2 RO*

ROL	F	M	K
RO ROL6	16.313	7.178	370
RO ROL600	17.177	7.558	390
RO ROL3.6k	17.924	7.886	386
RO ROL6k	21.054	9.264	246

Experimental values do not directly correlate to the models presented by Akter et al. [2] due to differences, such as wall and floor dimensions, fastener type, load on walls and the displacement induced, which resulted in a greater rotation of 0.05 rad.

4.2 OBSERVATIONS

General visual observation is that specimens do globally stay intact after being subjected to C1-C3. C4 however caused specimens to locally reach beyond elastic range. The plastic deformation is attributed to the increased displacement to achieve C4, which was governed by the software and hardware of the hydraulic actuator (3). In order to achieve C4 the displacement had to be greater than displacement at ROL C1-C3.

4.2.1 CLT

Most evident and immediately visible deformation was deflection of the floor, however no damage was identified visually as expected since the testing was planned to remain in the linear elastic range. Displacements of top and bottom walls, the lift and the drop under different ROLs are tabulated in Table 5 and Table 6 below.

Table 5: *Mean values of top wall vertical displacement (lift) LVDT1, where B1 indicates generic bracket (UoB) and B2 Rothoblaas (RO) bracket*

ROL	Mean (UoB)	Mean (RO)
C1	0.400	0.381
C2	0.484	0.423
C3	0.572	0.485
C4	0.722	0.690

Table 6: *Mean values of bottom wall displacement (drop) LVDT3*

ROL	Mean (UoB)	Mean (RO)
C1	3.870	3.926
C2	3.711	3.977
C3	4.107	4.169
C4	7.646	7.951

The bottom wall drops under the subjected loads. This results in opening between the floor element and the bottom wall as displayed in Figure 11. Consequently at C4 the strength perpendicular to the grain in the outer lamellas of the floor element was overreached and local crushing of the CLT occurred, because displacement was greater than in C1-C3. Figure 12 and Figure 13 display local crushing to the CLT.

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Figure 11: *Reversible opening for all ROLs when B2*

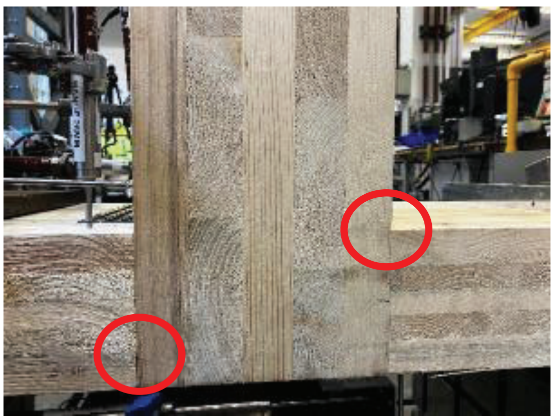

Figure 12: *Localised crushing to floor at both walls (specimen with generic bracket B1 UoB at C4)*

Figure 13: *Localised crushing to floor at the bottom wall (specimen with Rothoblaas bracket B2 RO at C4)*

4.2.2 Screws and brackets

No measurement on screws was undertaken but upon removal of the screws after the test no permanent deformation was observed.

No permanent deformation was anticipated and observed in metal brackets for ROL C1-C4, however generic bracket B1 plastically deformed under C4 as displayed in Figure 14.

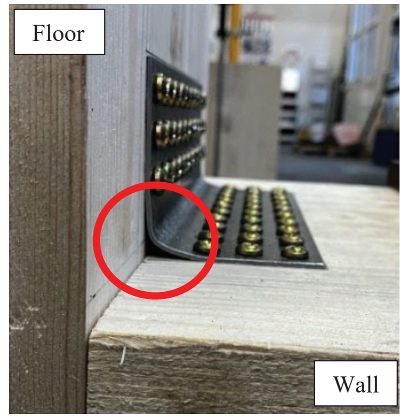

Figure 14: *Plastically deformed generic bracket (B1 UoB) when subjected to C4 and associated displacement*

5 CONCLUSIONS

Experimental studies of a typical wall-to-floor-to-wall (WFW) connection that can be found in a multi-storey building built in the platform type CLT construction were performed. Aim was to keep the specimens in the linear elastic range and to study how various rates of loading (ROLs) affect the CLT WFW connection.

Four different ROLs were used on two varied specimens. Most of the inherent material properties of timber, except the behaviour in compression, require designing in elastic range. When ROL C4 and associated displacement were applied to the specimens plastic deformation was confirmed as visible local crushing of outer lamellas of the floor element when in contact to the wall upon loading due to overreaching compressive strength perpendicular to the grain. Increase in stiffness at the achieved rotations might not be attributed to the ROL but to statistical error.

The outcomes of the performed tests will help with future testing scenarios where specimens will be tested beyond the elastic range and to failure and inform the development of future large scale system level study of the disproportionate collapse resistance of CLT platform type buildings. These are currently based on concrete and steel structures whereas slightly different behaviour is anticipated by CLT.

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