Seismic design of core-walls for multi-storey timber buildings

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ABSTRACT:

This paper describes options for seismic design of pre-fabricated timber core-wall systems, used as stairwells and lift shafts for lateral load resistance in multi-storey timber buildings.

The use of Cross-Laminated Timber (CLT) panels for multi-storey timber buildings is gaining popularity throughout the world, especially for residential construction. This paper describes the possible use of CLT core-walls for seismic resistance in open-plan commercial office buildings in New Zealand. Previous experimental testing at the University of Canterbury has been done on the in-plane behaviour of single and coupled Pres-Lam post-tensioned timber walls. However there has been very little research done on the behaviour of timber walls that are orthogonal to each other and no research into CLT walls in the post-tensioned Pres-Lam system.

This paper describes the proposed test regime and design detailing of two half-scale two-storey CLT stairwells to be tested under a bi-directional quasi-static loading. The test specimens will include a half-flight stair case with landings within the stairwell. The "High seismic option" consists of post-tensioned CLT walls coupled with energy dissipating U-shaped Flexural Plates (UFP) attached between wall panels and square hollow section steel columns at the corner junctions. An alternative "Low seismic option" uses the same post-tensioned CLT panels, with no corner columns or UFPs. The panels will be connected by screws to provide a semi-rigid connection, allowing relative movement between the panels producing some level of energy dissipation.

1 INTRODUCTION

Multi-storey timber structures are becoming increasingly desirable for architects and building owners due to their aesthetic and environmental benefits. In addition, there is increasing public pressure to have low damage structural systems with minimal business interruption after a moderate to severe seismic event.

Timber has been used extensively for low-rise residential structures in the past, but has been utilised much less for multi-storey structures. The use of timber in multi-storey construction has traditionally been limited to residential type building layouts which use light timber framing and include many walls to form a lateral load resisting system. This is undesirable for multi-storey commercial buildings which are usually characterised by large open spaces providing the client with versatility in their desired floor plan. In some cases timber is perceived as less durable and requiring regular maintenance. Due to these concerns there has been reluctance by clients and architects to use timber in multi-storey commercial structures.

As part of this research, options will be provided for architects and engineers to utilise timber walls around stairwells and lift shafts. To date little research has been done on timber stairwell and lift shaft cores (especially for the Pres-Lam system) and how they are incorporated into the lateral load resisting system of a structure. Commonly in multi-storey commercial buildings, the stairwell and lift-shaft cores are used as the main lateral load resisting elements. In many European countries timber buildings are required to have a concrete stairwell or lift-shaft core to provide a non-combustible exit route in the event of a fire (Muller 2010).

This paper presents the proposed experimental test set-up and design detailing of two 1/2 scale stairwell specimens incorporating post-tensioned CLT wall panels.

2 MOTIVATION FOR RESEARCH

In research previously conducted (Smith 2006, Newcombe *et al*. 2010) and continuing at the University of Canterbury (Sarti *et al*. 2013), single and coupled walls, loaded in plane are well understood. However there has been little investigation into how the Pres-Lam system could be incorporated into timber walls of different shapes, such as for the purpose of stairwell and lift shaft cores. A PRESSS (PREcast Seismic Structural System) concrete core has been investigated by Henry (2011) at the University of Auckland. However the system was only investigated analytically and no experimental testing was performed. This proposed research intends to use the experimental tests to provide practical guidelines for engineers and architects as to the use of the Pres-Lam system for a number of stairwell layout options.

The use of CLT is steadily growing in Europe (Ceccotti 2008) and Canada (Popovski *et al*. 2011, mgb *et al*. 2012) and is gaining traction in New Zealand since the commissioning of a CLT plant in Nelson by XLam Ltd. To date the primary construction method for CLT panels is to use screws or similar mechanical fasteners as the connectors. Popovski and Karacabeyli (2011) at FPInnovations in Canada investigated the seismic performance of CLT panels. A variety of panel and fastener layouts were investigated, however, all of the test specimens involved in-plane walls, no L or C shaped configurations. The performance of each specimen was determined and the results of two of the test specimens loaded cyclically are shown in Figure 1. Specifically (a) shows the performance of a panel with no additional axial load and (b) shows the performance of a panel with additional axial load. It can be seen in Figure 1 that the panels tested achieved an adequate level of ductility. However there is significant stiffness degradation caused by the plastic deformation of mechanical fasteners. Re-centring properties are also observed for the specimens with additional axial load (Figure 1 (b)).

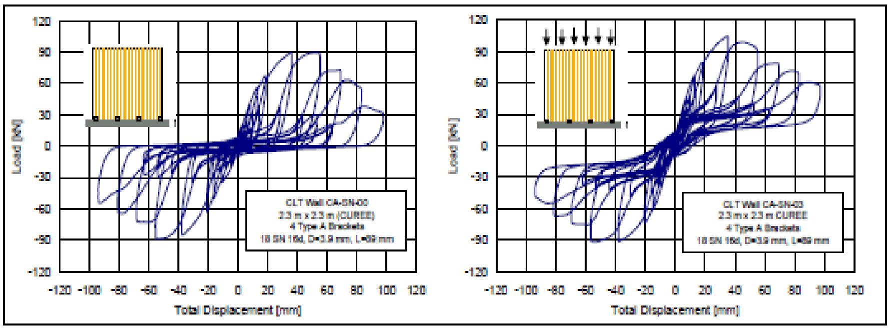

Figure 1: Results of two CLT wall configurations, (a) hysteretic behaviour of a wall with no additional axial load, (b) hysteresis for CLT wall panel tested with additional axial load (Popovski and Karacabeyli 2011)

Many of the buildings constructed using CLT to date have required many internal structural walls as discussed above. This research intends to show that by using CLT in the Pres-Lam system a more versatile building layout will be achievable. This research will investigate ways in which this can be achieved. A versatile CLT Pres-Lam system may help to increase use of CLT in multi-storey commercial buildings while providing a low damage seismic system.

3 PROPOSED EXPERIMENTAL TESTING

The experimental testing aims to refine and validate analytical models and design concepts for stairwell and lift shaft cores in multi-storey timber buildings. The testing also serves to demonstrate different options for energy dissipation and how a versatile system may be achieved. Two ½-scale two-storey stairwells will be tested under a quasi-static loading regime in the Structures Laboratory at the University of Canterbury. The two test specimens include a system aimed at a High seismicity region (Specimen 1, see Figure 2) and one aimed for a lower seismicity (Specimen 2, see Figure 3). The geometry of the test specimens are limited by laboratory constraints such as the operating height of the crane and the capacity of the hydraulic actuators.

Each of the specimens will be tested independently in the two major directions (long and short) and then a bi-directional loading under a cloverleaf protocol. Initially the two test specimens will be tested without a staircase. An internal staircase will then be added and the specimens will be tested again.

3.1 High seismicity option (Specimen 1)

The lateral load resisting system of the High seismic specimen is comprised of post-tensioned rocking CLT walls coupled with energy dissipation devices. The energy is dissipated by the deformation of U-shaped Flexural Plates (UFPs) attached between wall panels and the corner columns as shown in Figure 2 and further detailed in the following section. The corner columns will be square hollow steel sections. As the focus of the testing is not to look at the optimum seismic design, particular attention will be paid to the construction of the system and its seismic behaviour. The expected behaviour of the walls is shown below in Figure 4.

Beams representing the floor slab (see Figure 2) will be connected to the corner columns such that there are two beams running in the long direction and short direction of the stairwell. The beams represent gravity and drag beams respectively and are part of the floor diaphragm. It is proposed that the load be applied in two orthogonal directions through the two beams which transfer the lateral load to the columns. The post-tensioned wall panels will be in contact with the corner columns such that the load is able to be transferred into the walls by contact. The objective of applying the load through the columns and then into the walls is to minimise deformations of the flooring system. As the walls rock, one end of the walls will uplift. If the floor is connected directly to the rocking walls, the uplift may cause significant damage as the floor would need to bend out of plane.

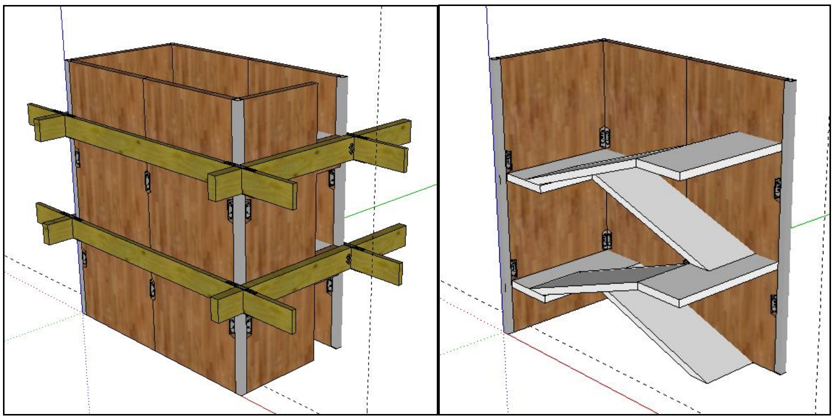

Figure 2: High Seismicity option (Specimen 1), showing the stair and landings. Post-tensioned CLT rocking walls with UFP devices and steel corner columns, tested at ½ scale

3.2 Low seismicity option (Specimen 2)

The primary objective of the Low seismic test is to investigate how the rocking system will perform with simple screwed connections. For this specimen, the same layout as the High seismic option with post-tensioned CLT walls will be tested as shown in Figure 3. Horizontal screws in single shear connect perpendicular panels. It is intended that the screws will connect the panels with a semi-rigid connection, such that when the walls rock, there will be relative movement between the wall panels. The relative movement will cause deformation in the screws which act as ductile fuses and result in some energy dissipation. In the long direction of the stairwell, the wall panels will be constructed with walls coupled side by side.

The main objective of the Low seismic option is to investigate the effect of the semi-flexible screwed connection on the overall behaviour of the stairwell, with increased numbers of screws in subsequent tests.

The quasi-static loading regime will be applied to the Low seismic specimen in a similar manner to the High seismic specimen. Loading beams will be connected to the walls as detailed below. However for this specimen, there are no boundary columns to connect the beams to. Therefore the beams will be attached directly to the parallel walls by pinned connections near the centre of each wall.

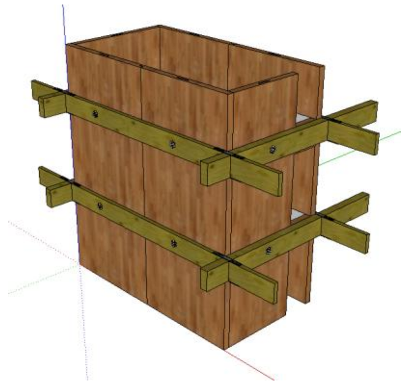

Figure 3: Low Seismicity option (Specimen 2). Post-tensioned rocking walls with screwed connections acting as ductile fuses, tested at1/2 scale

The expected displaced shape of the specimen is shown below in Figure 4. It is expected that there will be minimal deferential movement and uplift between the panels. Subject to desirable cyclic behaviour, an attempt will be made to increase the seismic performance of the system. This will have the objective of providing a cheaper alternative to the High seismic system. Further tests may also be performed to verify the performance of inserting additional screws as a retro-fit solution.

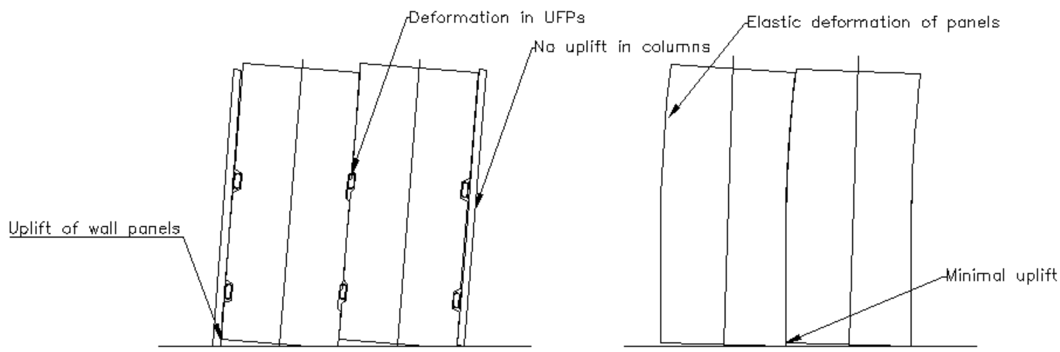

Figure 4: Expected displaced shape of the coupled walls for the High and Low seismic options

4 DESIGN DETAILING

The design of both the High seismic and Low seismic specimens is constrained due to limitations in the capacity of the strong floor and the vertical height of the Laboratory. As a result of this, the test specimens were detailed to be a two storey, one-half scale stairwell.

4.1 High seismic option

As described above, the High seismic option (Figure 5) comprises half-scale post-tensioned rocking CLT walls coupled with energy dissipation UFP devices and steel corner columns.

4.1.1 *Post-tensioned CLT walls*

The six CLT wall panels that make up the stairwell shaft are 100mm thick, approximately 1.6m wide and 3.75m long, made by XLam Ltd, Nelson, New Zealand. The cross-section of the panels is made up of five 20 mm layers, with three layers acting in the longitudinal direction and two acting in the transverse direction. A void in the middle layer, 200 mm wide, will be left such that a steel tendon can be inserted. These dimensions relate to full-scale walls with a cross-section of approximately 3.5m wide and 200mm thick. The design moment capacity of a pair of coupled walls along one side of the stairwell is 450 kNm at a design drift of 2.5% with corresponding floor forces of 120kN and 60kN acting at the top floor and the lower floor respectively. A five-storey post-tensioned timber case study building (STIC 2013) situated in Christchurch on soil class D, gave floor loads of 250kN and 125kN at the first and second floors. These floor forces, at half scale provided the design floor forces for the specimen. To achieve the required bending moment capacity, a single 15.2mm Super Strand tendon in each wall is required with an initial post-tensioning force of 110kN. This level of post-tensioning coupled with the UFP devices described below provides a re-centring ratio of 1.5. The single walls along the front, with the doorway opening, and the rear of the stairwell are designed to the same post-tensioning and re-centring level as the coupled walls.

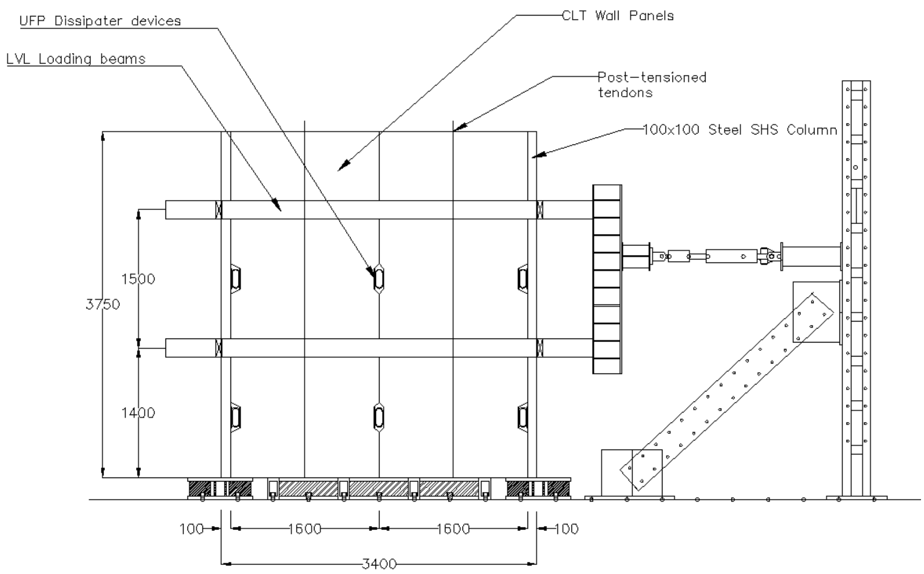

Figure 5: Side elevation of the High seismic option consisting of CLT wall panels, UFP devices and steel SHS corner columns. LVL loading beams included

4.1.2 *U-shaped flexural plate connections*

The UFP dissipater devices are designed such that the overall system has a re-centring ratio of 1.5 which corresponds to a required capacity of 30kN per UFP. Steel plates will be attached to the edges of the CLT panels with timber rivets (Zarnani and Quenneville 2013). The steel plates will have threaded holes in which the UFP device can be bolted onto the riveted plates as shown in Figure 6. The riveted plates are designed such that they will remain in the elastic range. If necessary during testing, the UFPs can be un-bolted and replaced.

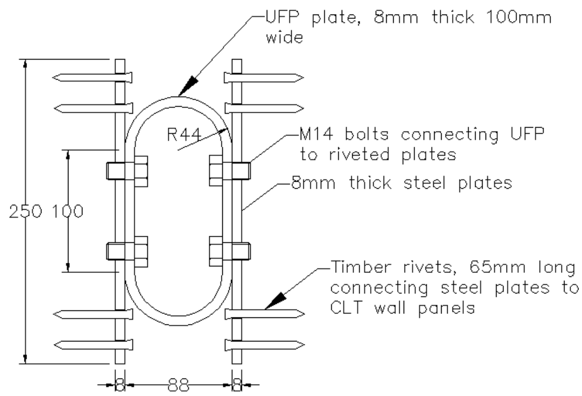

Figure 6: Detailing of UFP devices. UFP bolted to a steel plate that is riveted to the edge of the wall panels

4.1.3 *Loading beam connections*

As described previously, the load will be applied to the stairwell through loading beams, which are an idealisation of the floor diaphragm, transferring in-plane forces to the lateral load resisting system. The loading beams are connected to the steel SHS corner columns (Figure 7) with a ring of M16 bolts. The bolts will be screwed into threaded holes in the wall of the SHS column. This connection is a good approximation for a pinned connection as the oversized hole in the timber and the flexibility of the connection itself will allow for the column rotation. As the column bases are attached to the foundations, the loading beams will remain horizontal and hence no displacement incompatibility between the floor and the stairway core will occur. It should be noted that horizontal loads are transferred through the corner columns into the wall panels through direct contact.

The displacement incompatibilities and connections between the floor diaphragm and the lateral load resisting system are part of on-going research at the University of Canterbury (Moroder *et al.* 2013).

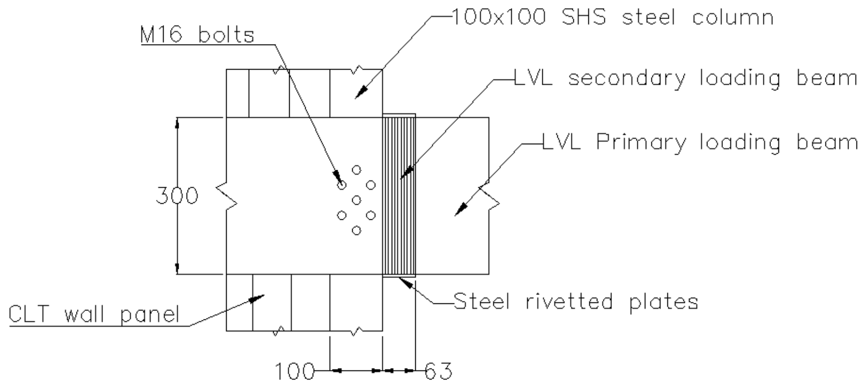

Figure 7: Bolted 'pin' connection between the loading beam and steel SHS corner column

4.2 **Low seismic option**

The Low seismic option (Figure 8) consists of post-tensioned rocking CLT walls interlocked with adjacent panels using simple screw connections. Details of the post-tensioned walls, screwed connections and loading beam connections are described below.

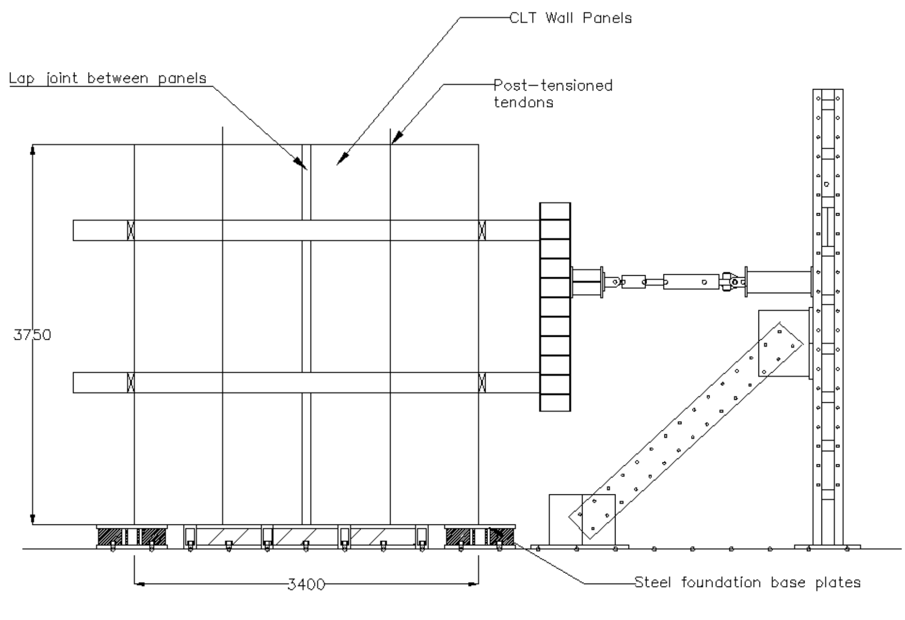

Figure 8: Side Elevation of the Low Seismicity option. Post-tensioned rocking walls with screwed connections and loading beams

4.2.1 *Post-tensioned CLT walls*

The six CLT walls used for the Low seismic option have the same cross-section as that of the High seismic option with five 20mm layers. The only difference between the panels used for the Low seismic option is that the panels along the long direction of the stairwell are 1.7m wide rather then 1.6m as is the case with the High seismic option as there are no 100x100 corner columns.

A single 15.2mm tendon with an intial post-tensioning of 110kN is to be used, consistent with the High seismic option.

4.2.2 *Screwed wall-wall connections*

Two types of screw connections are used between the CLT panels. A halved lap joint (Figure 9) connects the coupled walls with 6 mm diameter x 90 mm long screws. In the corners, a perpendicular screwed connection is also used (Figure 9) with 6 mm diameter x 200 mm long screws. In both of the screwed connection types, 25 screws are to be used up the height of the walls at 150 mm spacing providing the same shear capacity as the two UFPs used in the High seismic option. In the initial testing much fewer screws will be inserted to provide a semi-rigid connection with some movement. The number of screws will then be increased up to 25 screws along each joint.

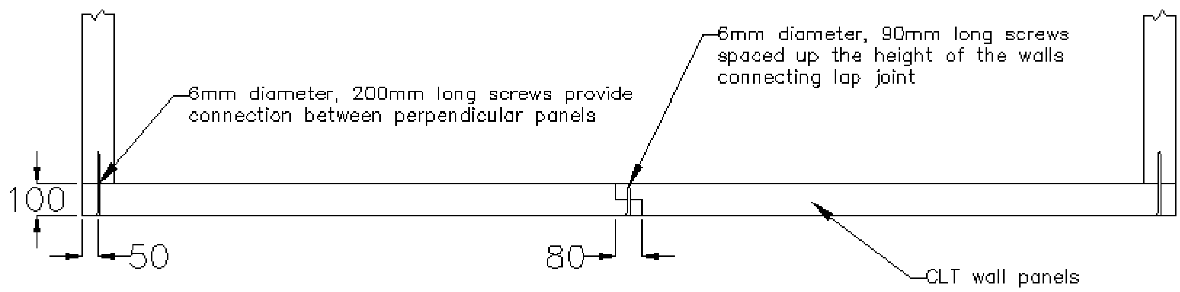

Figure 9: Screwed connections between panels with lap connection between coupled panels and connection between perpendicular panels

4.2.3 *Loading beam connections*

A ring of M16 bolts is used to connect the loading beams to the wall panels, as an idealised "pin" connection (see Figure 10). In this case, the loading beams are connected directly into the wall panels near the centre of the wall. For large drift levels displacement incompatibility will occur between the wall panels and the loading beams. Since the walls running perpendicular to the loading direction are not uplifting, the loading beams will bend, resulting in an out of plane bending at the floor level. Parallel research is carried out at this Institution to evaluate the effect of this incompatibility on the seismic behaviour of the wall and the performance of the floor diaphragm (Moroder *et al*. 2013).

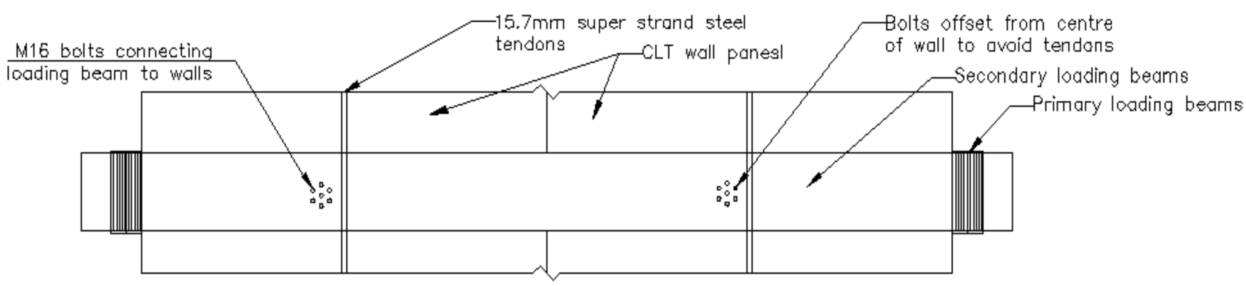

Figure 10: Bolted 'pin' connection between loading beams and the post-tensioned walls

4.3 Stair and landing connections

Half-flight stair and landings made from CLT panels will be included during testing of both the High and Low seismic options. The landings will sit on corbels screwed into parallel walls so that the landings span between the long walls of the stairwell. The stair panels will then be attached to the landings with a screwed bracket along the top of the stair. The bottom of the stair panel rests on the lower landing such that it is allowed to slide as the wall panels rock during seismic loading.

5 CONCLUSION

This paper describes the proposed testing and design detailing of two half-scale two-storey CLT stairwells including High seismic and Low seismic options. The High seismic option consists of post-tensioned CLT walls coupled with energy dissipating U-shaped Flexural Plates (UFP). The UFPs are attached between wall panels and between wall panels and the corner columns (square hollow section steel columns). The Low seismic option again consists of post-tensioned CLT panels; however with no corner columns or UFPs instead the panels will be connected by screws. The test specimens will include half-flight stairs and landings within the stairwell.

The key objective of this research is to provide structural engineers and architects with options for designing CLT walls for around stairwells and lift shafts of multi-storey timber buildings.

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