

PREVENTING SEISMIC DAMAGE TO FLOORS IN POST-TENSIONED TIMBER FRAME BUILDINGS**

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ABSTRACT

Post-tensioned rocking structures are known to perform well under seismic action, but as with most other structural systems, there is concern about possible damage to floor diaphragms. This is due to displacement incompatibilities, especially if frame elongation occurs due to gap opening at the beam-column-joints. This paper describes the experimental behaviour of an engineered timber floor connected to a post-tensioned timber frame subjected to horizontal seismic loading.

A full scale two-bay post-tensioned frame was loaded with lateral loads, which were applied through a strip of floor diaphragm spanning perpendicular to the beams. Several different connection configurations between the floor portions on either side of the central column were tested. The diaphragm deformation demand adjacent to the beam-column-joint gap opening was accommodated through two mechanisms: a concentrated floor gap opening at the column or a combination of panel elongation and small gap openings over a number of floor elements. In all the tests, only elastic deformations were observed and the diaphragm behaviour of the floor elements was fully maintained throughout the testing.

The results showed that design to allow flexibility of timber elements combined with proper connection detailing can prevent damage at high level of drift to the floor diaphragms in post-tensioned timber frame buildings.

1. INTRODUCTION

This paper provides a brief overview of the displacement incompatibilities in frame structures and summarizes related research work in concrete and timber buildings. A test setup of a two bay frame is described, followed by the test results. These are then discussed and conceptual design recommendations are given. Herein presented work focuses on timber-only floors in post-tensioned timber buildings, but the frame elongation problem is common in all types of frame structures, independent of materials.

1.1. STATE OF THE ART AND ADVANCES IN SEISMIC ENGINEERING

The targeted objective in performance-based earthquake engineering is life safety in the case of a major earthquake event. However, focusing on life safety

alone implies that structures and their contents will very likely be damaged, with a substantial financial impact in terms of repairing, rebuilding and lost income. An improvement is the trend towards a *damage control design philosophy*, found in the jointed-ductile systems in PRESS technology (PREcast Seismic Structural System), developed at the University of California at San Diego [14]. Whereas the columns, beams and walls are designed to be damage free, attention should be paid to the design and detailing of the connection between floor and lateral load resisting systems, as their behaviour and integrity could be compromised due to displacement incompatibilities.

All moment-resisting frame structures are subjected to the effects of beam elongation in the case of severe cyclic lateral loading. This is independent from the construction material and happens in traditional

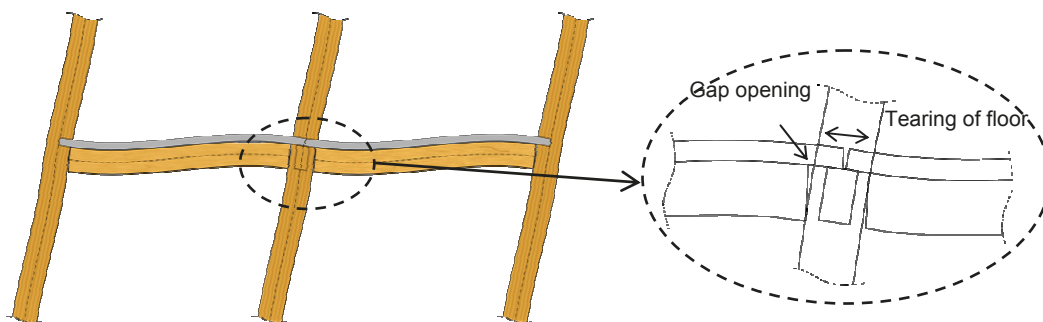


Figure 1. Tearing of the floor due to frame elongation resulting from beam-column-joint gap opening.

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Note: A full colour version of this article will be made available on the NZ Timber Design Society website (www.timberdesign.org.nz).

systems and also in jointed-ductile systems where the beam-column-joint gap opening is a desired peculiarity to provide damping via dissipation devices. Figure 1 shows how gap opening at the beam-column joint can cause tearing of the floor diaphragm.

The mechanisms of reinforced concrete frame elongation because of the formation of plastic hinges has been reported since the '70s and further studied in the '90s, but implications of these displacement incompatibilities on the design and behaviour of diaphragms have only recently been addressed by researchers [4, 5, 6]. Experiments by Matthews et al. (2003) simulated the collapse of precast flooring system because of beam elongation and the resulting pushing out of columns and beams (see Figure 2) [10]. Subsequent research by Lindsay et al. (2004) and MacPherson et al. (2005) led to detailing improvements to guarantee the diaphragm behaviour in the case of a seismic event; these solutions however still allow substantial damage [8, 9].

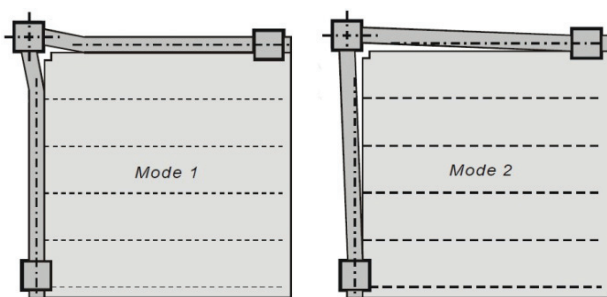


Figure 2. Particular deformation modes because of beam elongation [10].

A so called “non-tearing floor” solution has been proposed and tested by Amaris et al. (2008). His option includes complete avoidance of beam elongation by introducing a top hinge connection at the beam-column-joint or differential movement of the frame in respect to the diaphragm by providing sliding connection devices [2]. Au (2010), Leslie et al. (2010) and Muir et al. (2012) have been further developing the system, focusing on a slotted beam solution, which tends to eliminate frame elongation [3,7,11].

1.2. PRES-LAM STRUCTURES

The extension of the PRESS system to engineered timber has been developed in recent years at the University of Canterbury [13]. Some information regarding the floor diaphragm behaviour is provided by Smith et al. (2009) in the case of a beam-column subassembly connected to a portion of floor slab [15]. Newcombe et al. (2010) tested a 2/3 scale building under biaxial loading [12]. Both tests used timber-concrete-composite floors, whereas the tests in this paper used a “timber-only” floor with no concrete topping. Specific experiments and design solutions for the seismic diaphragm performance of timber-only floors have not been addressed to date.

The experimental investigation presented in this paper shows the integrity of a timber-only engineered floor during quasi-static cyclic loading up to a drift level of 3.5%. The flexibility of timber, combined with proper connection detailing, allowed for displacement incompatibilities by providing either:

1. A concentrated gap in the floor near the beam-column-joint by connecting only the bottom part of the adjacent floor joists;
2. A number of smaller gaps between several floor elements combined with the elongation of the timber-only floor panels.

2. EXPERIMENTAL TESTING

2.1. TEST SPECIMEN

The full scale, two-bay frame shown in Figure 3 was assembled with engineered timber-only floor sitting on top of the main beams. The frame was loaded by applying horizontal forces to the floor elements.

The frame with bay lengths of 6 m consisted of three solid columns (288 x 500 mm) and two hollow beams (288 x 360 mm), where the webs and flanges were made of 45 mm elements. All elements were made of LVL11. The beams were sitting on steel corbels and connected to the columns by four 7-wire pre-stressing strands (diameter 12.7 mm) tensioned up to 100 kN. The draped profile of the post-tensioning was intended for the gravity design of the frame used in earlier testing [16].

To simulate the timber-only floor diaphragm, seven 2 m long floor panels were mounted on top of the beams. These were designed as stressed-skin-panels for a span of 7.4 m resisting a dead load of 2 kN/m² and a live load of 3 kN/m². The top skin was a 36 mm cross-banded LVL panel, the internal and external joists were 90 x 290 mm and 45 x 290 mm respectively. The joists and, where present, the blocking, were connected to the top skin by nail-gluing, using 3.3 x 90 mm gun-nails at 50 mm centres. The blocking was necessary to transfer the horizontal shear forces from the diaphragm to the beams through panels 2-4 and 7. These 45 x 290 mm blocking elements were connected to the web of the beams by steel plates with ø8 x 80 mm Spax screws and M10 bolts respectively. It was assumed that the diaphragm had to carry a shear force of 20 kN/m, hence the single floor elements were connected to each other by using 45° inclined ø6 x 120 mm fully threaded Spax screws at 150 mm centres.

With this setup only limited diaphragm action can be achieved in the floor panels as the load application is close to the beam. The shear flow in between the panels is given by the in-plane bending of the panels rather than from a diaphragm behaviour, but is still considered representative enough.

As the behaviour of the floor at the position of the central column (circled in Figure 3) was of main interest, the

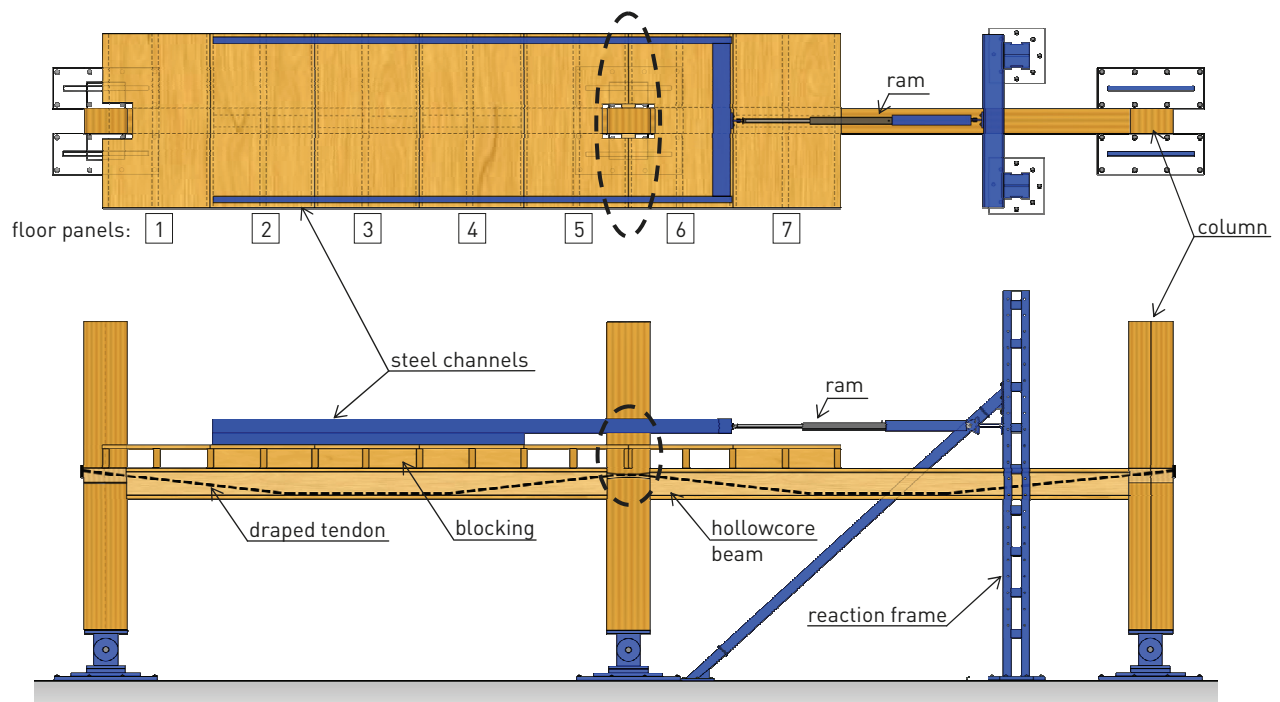


Figure 3: Test setup of the 2 bay frame with floor panels

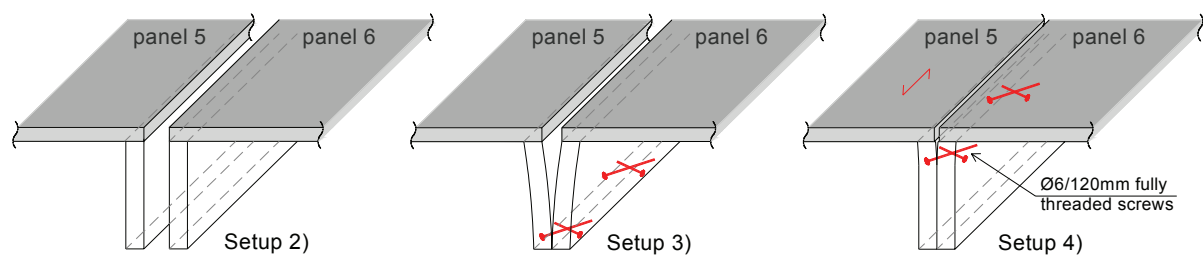


Figure 4: Connection of floor elements at the central beam-column joint: Setup 2) no connection; Setup 3) bottom flange connection; Setup 4) top flange connection

specimen was tested by considering the following four setups, summarized in Figure 4:

1. Frame without floor elements (i.e. the frame is loaded directly);
2. Floor elements at the central column are not connected, i.e. left and right portion of floor elements can slide respectively to each other;
3. Panels 5 and 6 are connected at the bottom of the external joists by fully threaded screws;
4. All panels are connected at the top of the joist by fully threaded screws.

The first test, Setup 1, is a benchmark test to study the behaviour of the frame. Setup 2 was necessary to measure the amount of floor gap opening to expect and does not guarantee diaphragm action. The two successive connection details Setup 3 and Setup 4 provided the *concentrated* and the *spread gap solutions* respectively.

2.2. TEST SETUP AND LOADING PROTOCOL

The frame was loaded in horizontal loading through the floor panels 2, 3 and 4. Figure 5 shows the quasi-static

cyclic loading protocol, based on ACI 374.1-05, omitting however the small cycles in between the 3 repetitive cycles [1].

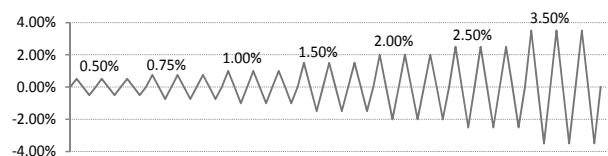


Figure 5: Quasi-static cyclic loading protocol

Linear displacement potentiometers were used to measure the gap opening at the beam-column-joints and between the floor panels, as well as any elongation of the panels.

3. RESULTS

Figure 6 shows the force-displacement curves for all four test setups together with the level of post-tensioning force. Figure 7 shows the central beam-column-joint gap opening together with the gap opening between panels 5 and 6 and the elongation of panel 5 for Setup 3. Figure 8 shows the gap opening of all floor

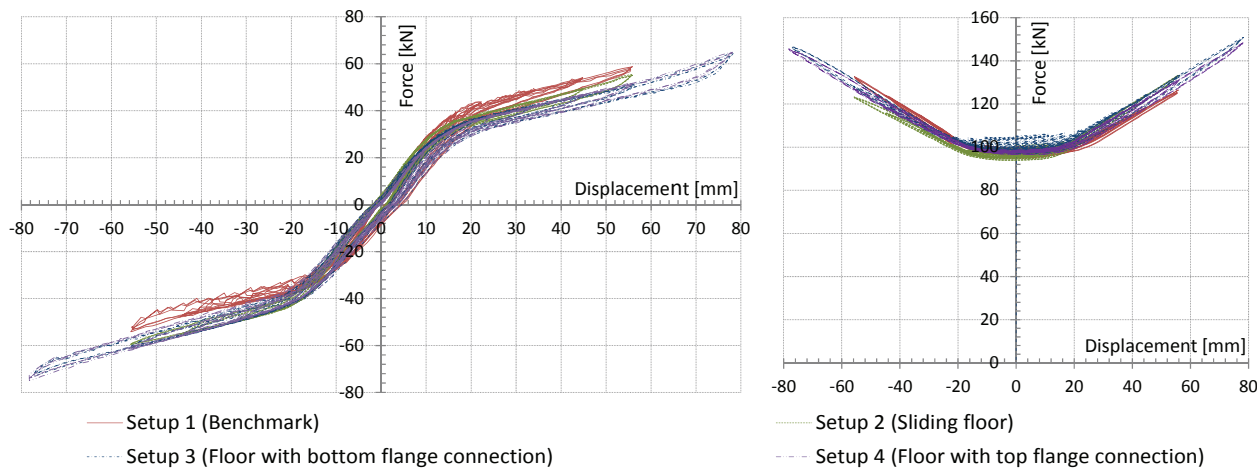


Figure 6. Force-displacement curve (left) and post-tensioning force (right).

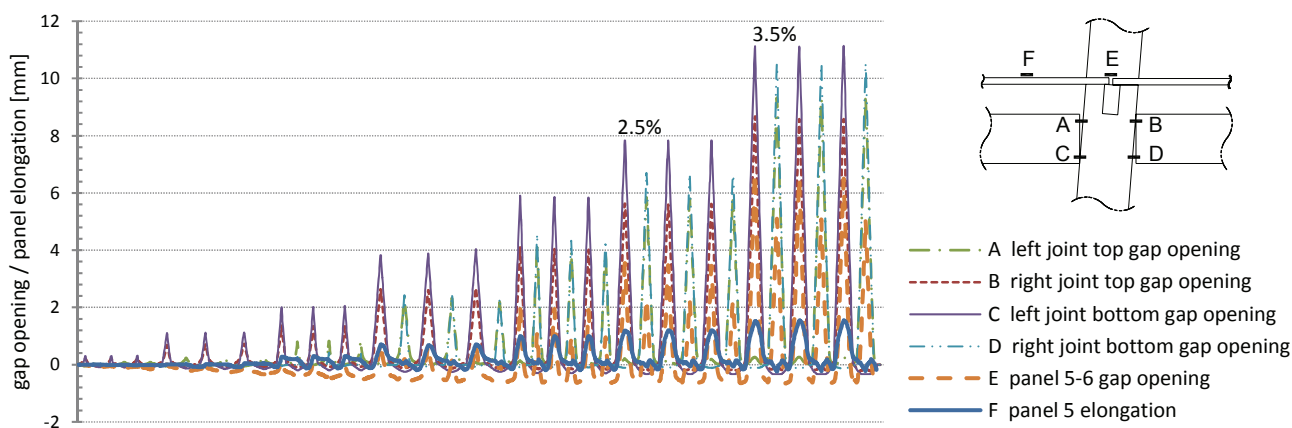


Figure 7. Central beam-column-joint gap openings overlaid with the gap opening between floor panels 5 and 6 and the elongation of floor panel 5 (Test Setup 3 – concentrated floor gap opening).

elements for Setup 4. Table 1 summarizes the key values for all four setups.

To show the performance of the post-tensioned frame and to provide data to evaluate the influence of the diaphragm, the global force-displacement curves of the frame and the increase of the force in the post-tensioning strands have been overlapped in Figure 6. For test Setups 1 and 2 the frame was loaded up to 2.5% drift, for Setups 3 and 4 the frame was pushed to 3.5% drift.

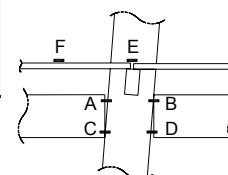
Figure 7 shows the beam-column-joint gap opening behaviour at the central column for Setup 3. Also shown

is the gap opening between panels 5 and 6; all other floor panel gap openings are close to zero. The elongation of floor panel 5 is shown as well, with similar values for panel 6 (not shown).

Test Setup 2 shows similar behaviour to Setup 3. From Table 1 however, it can be seen that the floor gap opening is much higher in Setup 2. This is expected as the floor panels 5 and 6 are not connected to each other. As all required deformation is provided by the gap, the panel elongation is close to zero. The beam-column-joint gaps are identical for both setups.

Table 1: Key values in mm for all four setups for 2.5% drift (values in parenthesis are at 3.5% drift)

Test Setup	Beam-column-joint gaps				Panel	
	top left A	top right B	bottom left C	bottom right D	gap 5-6 E	elongation F
1	4.89	6.05	8.31	7.00	n.a.	n.a.
2	5.72	6.14	7.85	6.13	6.58	0.31
3	5.85 (9.33)	5.63 (8.68)	7.84 (11.14)	6.70 (10.52)	3.55 (6.71)	1.20 (1.56)
4	5.79 (9.29)	5.27 (8.23)	7.74 (11.23)	6.87 (10.75)	1.09 (1.91)	1.77 (2.39)



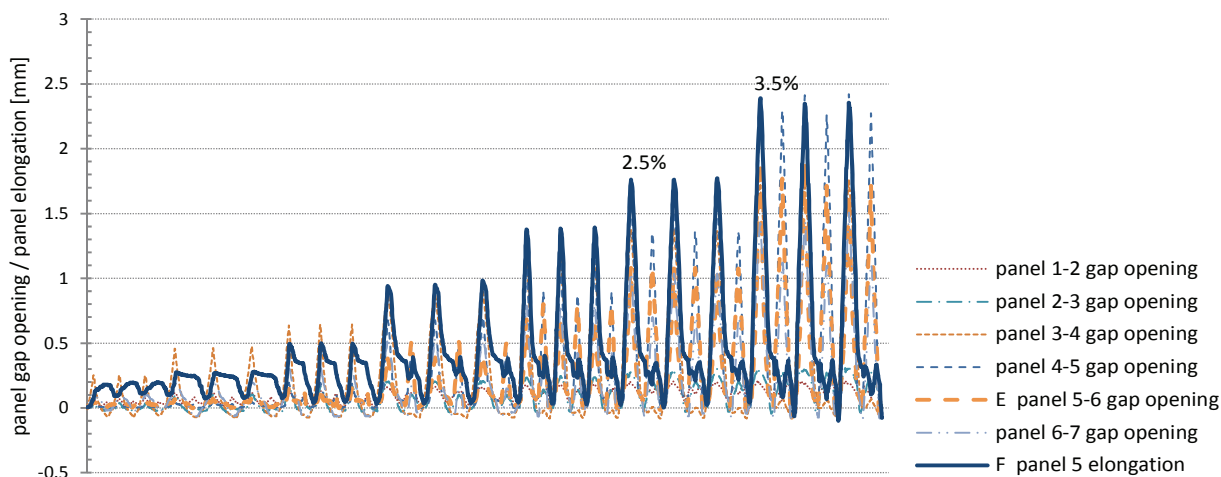


Figure 8: Gap opening of the different floor panels and the elongation of floor panel 5 (Test Setup 4 – spread floor gap opening and panel elongation)

Results for Setup 4 are plotted in Figure 8. The beam-column-joint gap openings are not shown as they are identical with Setup 3 (compare Table 1). All floor gap openings together with the elongation of panel 5 are shown. The gap openings close to the beam-column-joints are bigger and tend to zero for panels further away from the disturbed area. Whereas the gap between panels 5 and 6 is smaller than in test 3, the panel elongation becomes more dominant.

Table 1 shows that the beam-column-joint opening is about 6 mm at the top and about 7 mm at the bottom for all setups. The difference between top and bottom values is caused by the draped profile of the tendon and the resulting pre-camber of the beam.

4. DISCUSSION AND DESIGN RECOMMENDATIONS

4.1. INFLUENCE OF THE DIAPHRAGM ON THE FRAME BEHAVIOUR

The results from Setups 1 and 2 shown in Figure 6 indicate that the frame has the same behaviour if loaded directly via the beam or through the floor diaphragm. The negligible difference in stiffness and strength is given by the higher loading point (the diaphragm level is above the top of the beam) and by the slightly different initial post-tensioning force applied.

Also for test Setups 3 and 4, where the floor elements are connected to each other, there is no significant difference in the global behaviour of the frame. This means that even though tearing forces tend to move the floor elements apart, no stiffening of the overall structural system occurs and the performance of the frame remains unaffected.

4.2. PERFORMANCE OF DIFFERENT CONNECTION DETAILINGS

For the bottom flange connection (Setup 3) the floor elements 5 and 6 can move apart by transverse bending of the LVL joists over their height. This behaviour can be

clearly seen in Figure 9. By comparing the values in Table 1 it can be seen that the beam-column-joint gap openings remain essentially the same, another indication that the presence of the floor does not interfere with the overall performance of the frame. Because of the flexible connection, the floor gap opening tends to be smaller than in the case of the totally unconnected Setup 2 (3.6 mm and 6.6 mm respectively for a drift ratio of 2.5%). The remaining displacement is taken by the internal elongation of panels 5 and 6 (about 1.2 mm for a drift ratio of 2.5%) and some additional smaller floor gap openings in adjacent panels.

By connecting the floor elements by a much stiffer top flange connection (Setup 4), the imposed displacement cannot be taken solely by a single concentrated gap, but is spread out over several floor elements. This can be clearly seen in Figure 8, where the magnitude of floor gap openings is smaller, but occurs in more positions,

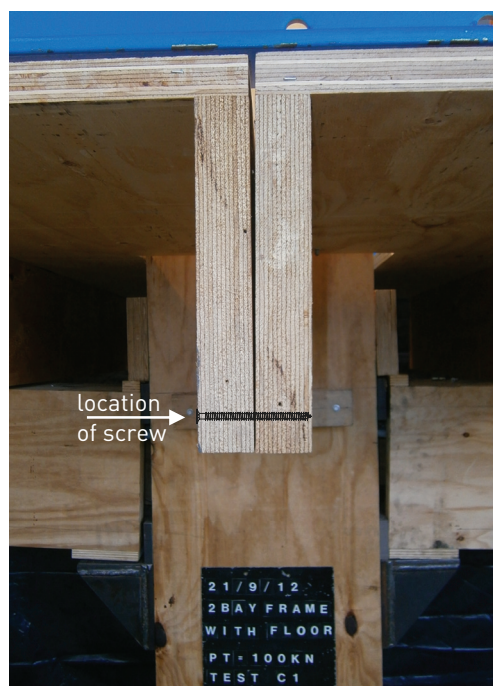


Figure 9: Floor gap opening 5-6 during test Setup 3 (concentrated gap solution).

with higher values close to the central column. Additionally the panel elongation is notably higher than in Setup 3 (2.4 mm instead of 1.6 mm for 3.5% drift); this behaviour is expected also in panel 6 and in a lesser extent in adjacent panels. By summing up the single floor gaps and the panel elongations, the displacement required from the beam-column-gap opening can be obtained.

After unloading the frame, no residual deformation or damage in the timber elements or connections could be observed. This can be explained by the flexibility of the timber elements and their connections.

4.3. CONCEPTUAL DESIGN RECOMMENDATIONS

Depending on the flexibility of floor finishings and linings of adjacent internal and external walls to move with the floor, the designer can choose from 2 solutions to accommodate the displacement in the floor diaphragm:

- **Concentrated floor gap:** The required deformation should occur mainly in a single gap between floor panels, which will need special detailing. If the floor joists are flexible enough in transverse bending, a bottom flange connection with screws is sufficient. The connection still needs to guarantee the full shear transfer between the panels. If required, special steel elements, which allow the panels to move apart, can be used. Seismic gaps in the floor finishing and the wall linings may have to be provided.
- **Spread floor gaps and panel elongation:** All floor panels can be connected to each other by metallic connectors like nails or small diameter screws, which give some local flexibility. The connections need to guarantee the full shear transfer between panels. Gluing to connect floor

panels should not be used, as it results in a very stiff and brittle connection, which cannot accommodate the required deformations. The panels close to the disturbed area should not be directly connected to the beam, as this would prevent the development of gap openings and panel elongations further away from the beam-column joint. The diaphragm to beam connection should not be a brittle type of connection. The floor finishing should be chosen to be elastic enough to allow for the formation of spread gaps or might require some cosmetic repair after a major seismic event.

A timber-concrete-composite floor should be designed using the concentrated floor gap option. The concrete topping should be pre-cracked along the required gap line. Instead of providing continuous steel reinforcement over the crack, the shear transfer can be obtained by dowel action of unbonded rebars. Contrary to the timber-only solution, the deformation of the steel rebars might give some additional strength and stiffness to the frame. Special care will be required if the position of the crack corresponds with the connection line between the concrete slab and a beam. If the latter acts as a chord or collector beam, the formation of cracks might prevent the proper transfer of forces.

5. CONCLUSIONS

This paper provides an overview of the displacement incompatibility issues between floor and lateral load resisting system encountered in frame structures, with focus on timber buildings. Based on experimental testing, conceptual design recommendations for timber floor diaphragms are also suggested. Results from a

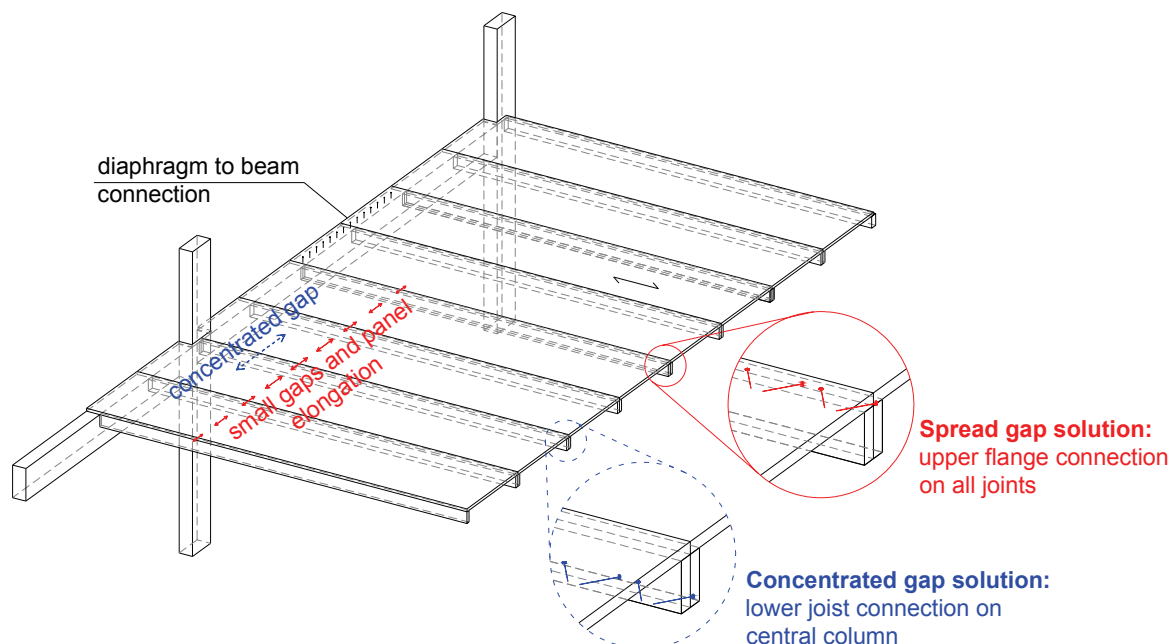


Figure 10: Alternative designs for a concentrated floor gap solution and a spread floor gap and panel elongation solution in an engineered timber floor.

full-scale two bay post-tensioned timber frame loaded under quasi-static seismic loading through a timber-only engineered floor diaphragm show that:

- The presence of the floor diaphragm does not affect the structural behaviour of the frame itself;
- The flexibility of the timber-only floor elements and their connectors are able to accommodate the frame elongations. The required displacement at the floor level was guaranteed without any noticeable damage and without comprising the diaphragm behaviour.

Two different connection details are proposed:

- *Concentrated floor gap* at the position of the beam-column-joint (this is also the solution for a timber-concrete-composite floor, but this was not been tested in this test programme);
- *Spread floor gaps and elongation* of the floor diaphragm over several floor panels.

The experimental setup presented in this paper was not capable of investigating the diaphragm behaviour of a whole building, as it would have required the setup of a full scale diaphragm between a second frame, which was not possible at this time.

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