Experimental testing of alternative beam-column joints in post-tensioned timber frames

T. Armstrong, T. Smith, A.H. Buchanan & S. Pampanin,

Department of Civil Engineering, University of Canterbury, Christchurch.

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ABSTRACT: Post-tensioned timber structural technology, known as Pres-Lam, has matured to the point where it is now transitioning from the laboratory to the construction site. An extensive testing programme at the University of Canterbury has shown these systems provide excellent seismic resistance, by combining energy dissipation and re-centering. Detailing of the joint zone to ensure both cost effectiveness and seismic performance is critical to the commercial uptake of this technology.

This paper details the experimental investigation of a full scale beam-column joint at the University of Canterbury. The testing involved several connection details which considered alternative energy dissipation devices and various methods of joint armouring. Joints were subjected to cyclic loading up to 3% drift. Joint details were evaluated, assessing ease of design and construction, re-centering ability, energy dissipation and cyclic stability. An investigation into the replaceability of dissipative elements has been undertaken to assess both ease of replacement and possible deterioration of seismic performance.

1 INTRODUCTION

Several Pres-Lam timber framed buildings are being constructed as part of the rebuild after the Christchurch earthquakes. They can provide advantages including:

- re-centering behaviour; limiting residual deformations in the structure,
- weight reductions; reducing seismic forces and lowering foundation requirements, and
- ease of erection; limiting construction time (Smith et al., 2008).

Particular care must be taken in detailing the beam-column joint connection, including armouring of the timber in the column, and the connection of discrete energy dissipating devices.

This paper summarises the experimental campaign to investigate beam-column joint behaviour and provides guidance to the designers of these connections.

2 SPECIMEN DESIGN

The test specimens were designed around a reinforcement option for the LVL in the column. Each of the specimens was tested both with and without external dissipation devices. The initial test setup was slightly modified from a joint being used in the Merritt Building, designed by Kirk Roberts and under construction in Christchurch. Subsequent specimens were designed to match the moment-rotation performance of this building’s design. The one-bay frames in this building provided a challenge to the designers because of very high gravity loads in addition to the seismic loading, whereas a frame dominated by seismic loading would have a more symmetrical distribution of bending moments.

2.1 Test Specimens

Joint reinforcement and dissipation options were combined to create each test specimen. These combinations are summarised in Table 1.

The testing considered both steel-based and screw-based options for reinforcement of the column where the wood is stressed in compression perpendicular to the grain. Exploded views of these two options are shown in Figure 1 and Figure 2. The steel reinforcement option was fabricated by commercial suppliers, while the screw-based option was constructed in-house.

Table 1. Summary of Tested Combinations of Reinforcement and Dissipation

Joint Reinforcement	Dissipation	Dissipater Connection
Steel	None	-
	Necked Rod	Threaded Coupler
	Necked Plate	Bolted Rivet Plate
Screws	None	-
	Necked Plate	Proprietary Screw Anchorages
	Timber Encased	Inclined Screws

2.2 Joint Reinforcement

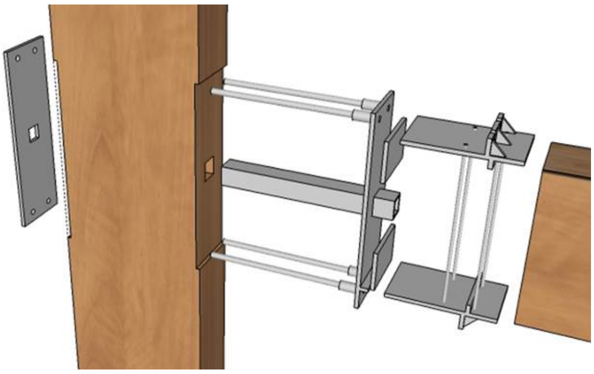


Figure 1. Steel-based joint reinforcement

Figure 2. Screw-based joint reinforcement

2.3 Steel-Based Reinforcement

The first joint tested used steel plates, steel rods and a hollow steel section to reinforce the LVL in the column, as specified for the Christchurch building, so the initial test specimens were designed to match the response of that building. The design of the whole building relied on some re-centering from the large gravity loads, hence the individual beam-column joints were not required to be fully re-centering on their own. As a result, the post-tensioning forces were lower and the effect of dissipation was larger, in the tested joints compared with designs where the post-tensioning alone would provide full re-centering of the joint.

2.4 Screw-Based Reinforcement

A second joint reinforcement option used long fully threaded screws. These acted similarly to piled foundations to diffuse compressive forces due to rocking over a larger area. Additional screws were also provided to counteract medium and long-term creep in the joint zone due to post-tensioning stresses.

This reinforcement scheme was fabricated in-house, requiring considerable time and effort. The construction would be greatly improved with the use of CNC fabrication techniques to drill the necessary pilot holes for the screws. This technology is now becoming available in the New Zealand market.

2.5 **Energy Dissipation Devices**

Discrete energy dissipation devices were included with the tested specimens. These functioned as a fuse, effectively concentrating all damage into easily replaceable elements. A common feature of all the options is that mild steel was forced to yield over a well-controlled, specified length and sectional area. These two properties are chosen by the designer and allow force-displacement behaviour to be well defined at the design stage. The low variability of the mechanical properties of mild steel make it well suited for this application where the dissipater strength must be controlled within precise limits.

2.6 **Necked Rod Dissipaters**

Necked Rod Dissipaters consist of threaded rods with a turned down region in the centre. These are surrounded by a steel sleeve which is filled with grout or epoxy to restrain buckling. This arrangement is shown in Figure 3. These dissipaters performed well, with no buckling noted during testing for either filler material. The dissipaters were connected to the joint using threaded couplers which were connected to epoxied rods that ran fully through the joint and were anchored on the outside faces as shown in Figure 1. The rod and coupler arrangement is shown in Figure 3.

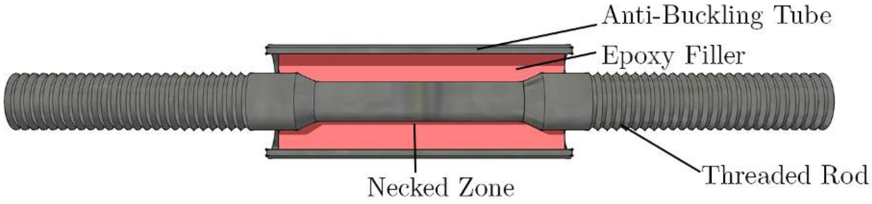


Figure 3. Cutaway view of Necked Rod Dissipater

2.7 **Necked Plate Dissipaters**

Necked Plate Dissipaters are flat steel bars which have been milled to provide a central yielding zone, as shown in Figure 4. Previous research into mild steel dissipaters (Smith et al., 2013) has shown that sharp transitions down to the necked area reduce cyclic performance, so a smooth radius was used as shown in Figure 4.

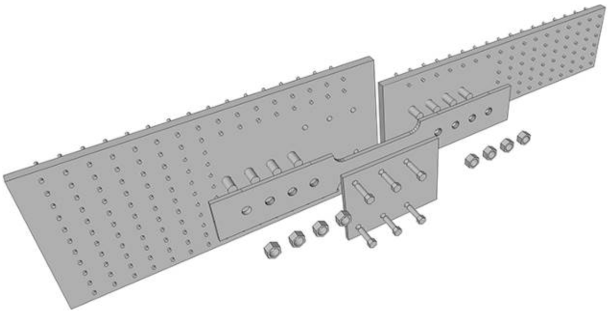
Figure 4. Necked Plate Dissipater

Necked Plate Dissipaters were connected to the joint using several different connection systems, including timber rivets (Quenneville & Zarnani, 2013) and proprietary ZD tension-compression anchorages using inclined screws (SWG Schraubenwekr Gaisbach GmbH., 2011).

a) Short Screws

b) Long Screws

c) Full Length Cover Plate



d) Bolted Rivet and Cover Plate

Figure 5. Anti-Buckling Options for Necked Plate Dissipaters

As these thin plates are designed to yield in tension and in compression, buckling is a significant issue which must be addressed by the designer. The tested dissipaters used additional cover plates to restrain against buckling. For the riveted connection, cover plates were bolted into threaded holes in the rivet plate. The screw anchor design used several configurations of plates which clamped over the necked region. These are summarised in Figure 5.

2.8 **Timber Encased Dissipaters**

Timber Encased Dissipaters comprise threaded steel rods with a necked region epoxied into an LVL block which provides anchorage for the bars and buckling resistance when loaded in compression, as shown in Figure 6. These dissipaters were fabricated in-house. LVL sheets were glue-laminated using the procedure from the Screw-Lamination Design Guide (EXPAN, 2012). Necked, threaded rods were inserted into routed slots which were filled with low viscosity epoxy resin. The blocks were then attached to the beam and column with inclined screws installed at 60° to the grain to enable them to act mainly in tension rather than shear. This produced a stronger, but more importantly to the dissipaters performance, much stiffer connection than screws perpendicular to the wood surface.

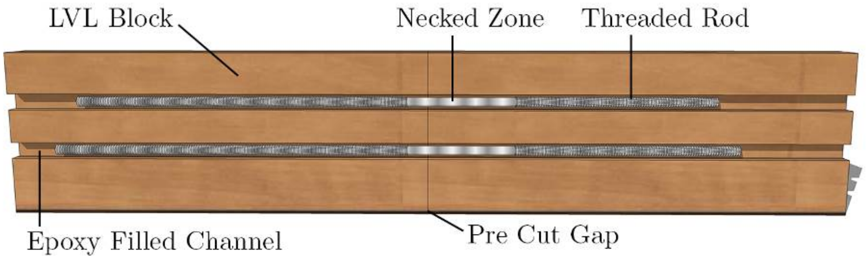


Figure 6 Timber Encased Dissipater

3 **EXPERIMENTAL SETUP**

3.1 **Apparatus**

The specimen was horizontally loaded at the mid storey height through a hydraulic ram and loading beam. Pin connections were used to ensure no induced moment. The column was pinned at the base using a rocking foundation plate. The beam was supported at the free end with a dual pinned mechanism, allowing horizontal translation and rotation but no vertical displacement. A schematic view is shown in Figure 7.

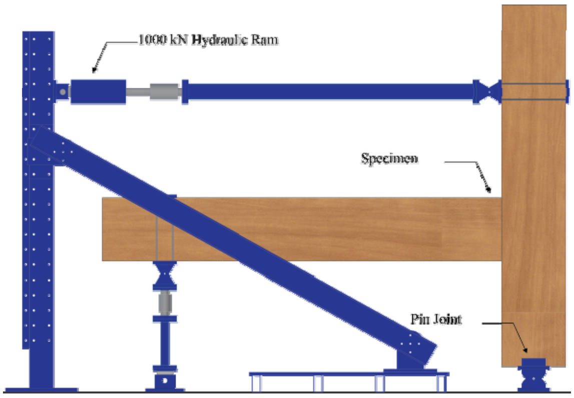


Figure 7. Test apparatus setup

Figure 8. Photo of test setup

3.2 **Loading Protocol**

The joint was subjected to a unidirectional, cyclic displacement, applied at the mid-storey height of the column. The displacement was fully reversing, up to a peak of 3.0% drift. The displacement history followed a modified ACI (ACI, 2001) protocol, similar to that used in other tests of Pres-Lam joints (Newcombe et a1., 2010), (Iqbal et al. 2010).

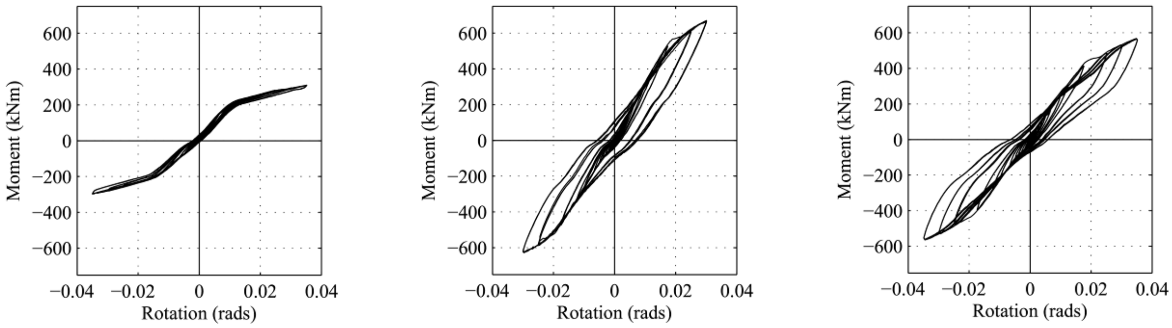
4 TEST RESULTS

4.1 Moment Rotation Performance

The moment-rotation behaviour of the joints is the key descriptor of performance. The plots in Figure 9 and Figure 10 show the data recorded for each test. These clearly show both the re-centering and dissipative components of the behaviour.

The joints using steel reinforcing were only designed for partial re-centering. This is evident by the moment-rotation loops not returning through the origin. The screw reinforced joints were designed to be fully re-centering. A trade-off must be made between the energy dissipation and re-centering capabilities of a joint targeting a specified moment capacity as the area contained within loops gives the total dissipated energy of the system.

As expected, the joints without energy dissipaters produced loops containing minimal area. These joints produced a more well defined change of stiffness at gap opening that those with dissipaters. This was due to the multiple yielding points in such systems.

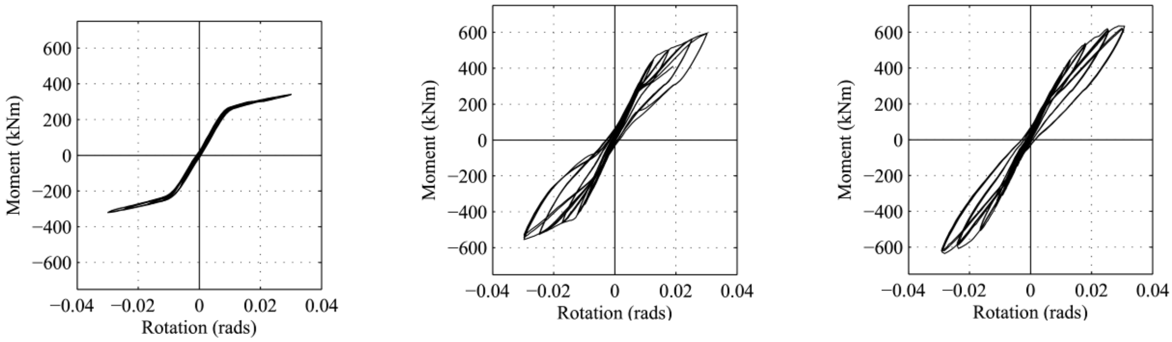


a) No Dissipation Devices

b) Necked Rod Dissipaters

c) Necked Plate Dissipaters

Figure 9. Moment - Rotation Results for Steel Reinforced Joints



a) No Dissipation Devices

b) Necked Plate Dissipaters

c) Timber Encased Dissipaters

Figure 10. Moment - Rotation Results for Screw Reinforced Joints

4.2 Post-tensioning Activation

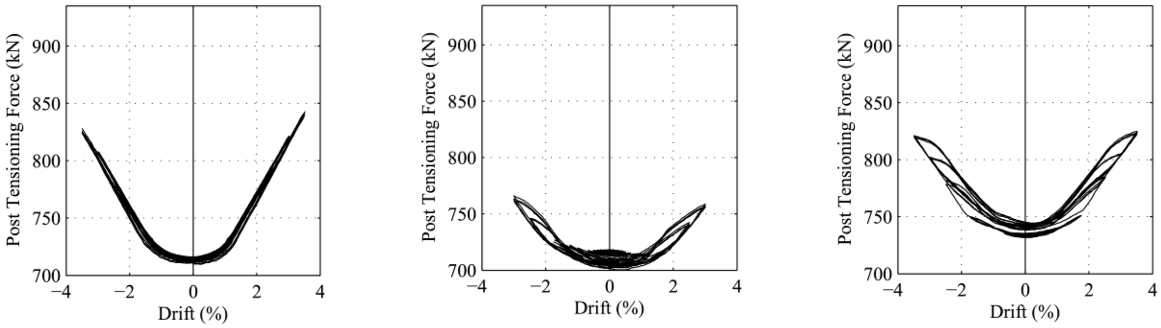
Gap opening behaviour in the joint produces a geometric non-linearity in the system. This is apparent in the plots of post-tensioning vs. drift in Figure 11.

All of the joints tested produced good post-tensioning activation relationships. This can be seen in

Figure 11 and Figure 12. The loops exhibited well defined and cyclically stable behaviour. A slight asymmetry in the response was seen in some of the joints. This was thought to be due to interference from dissipation devices and shear keys in the joint. An average of the two responses is expected in whole frame behaviour as the joint rotations will oppose each other at the two ends of each beam.

The joints designed with screw-based reinforcement were designed to be fully re-centering. Because of this, the initial post-tensioning force was greater than for the steel reinforced joints. This can be seen both in plots of the post-tensioning activation and moment-rotation behaviour.

The initial post-tensioning force for each specimen was 5% to 10% below the target value of 750kN for the steel reinforced specimens and 810kN for the screw-based joints. This affected the moment capacity of the joints. For the most severe case, Necked Plate Dissipaters on the steel reinforced joint, moment capacity was 8% lower than designed for. Post-tensioning was observed to fluctuate daily, and was correlated to temperature and humidity. As structures are unlikely to experience an earthquake immediately after construction, they too are likely to have reduced post-tensioning forces. Designers should take this into account, ensuring maintenance plans are in place to ensure adequate post-tensioning over the building's lifetime.

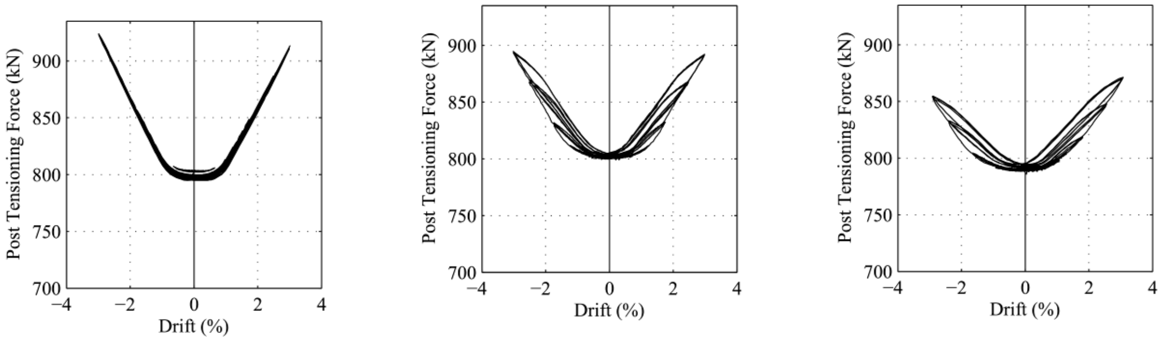


a) No Dissipation Devices

b) Necked Rod Dissipaters

c) Necked Plate Dissipaters

Figure 11. Post-tensioning activation for Steel Reinforced Joints



a) No Dissipation Devices

b) Necked Plate Dissipaters

c) Timber Encased Dissipaters

Figure 12. Post-tensioning activation for Screw Reinforced Joints

4.3 Damage Observations

Only very minor damage was observed to the joints tested in this programme, mainly concentrated around connections to the dissipation devices. The damage was considered to be largely aesthetic as there was no evidence of it in the performance of the joints. Three minor issues are discussed below.

During a test using necked rod dissipaters on the steel reinforced joint, at a drift of 0.5% cracks were noticed at the end of the steel plate on the beam. Testing continued to a drift of 2.7% where a sudden separation of the epoxy under the plate was observed, due to bending of the plate as shown in Figure 13 and Figure 14. This may have been caused by minor displacement incompatibilities between the

LVL column and the internal steel reinforcing. After a visual inspection following the test, it was decided that this damage was primarily aesthetic and did not affect the load path of the dissipaters. Subsequent tests using this joint displayed no reduction in performance..

Some buckling, shown in Figure 14, was also seen in the necked rod dissipaters at large displacements. The moment-rotation plot of this test does not show significant degradation due to this effect, so it is not a critical weakness, especially as seismic events typically contain relatively few large pulses. However careful detailing should be used to prevent this type of deformation in future designs.

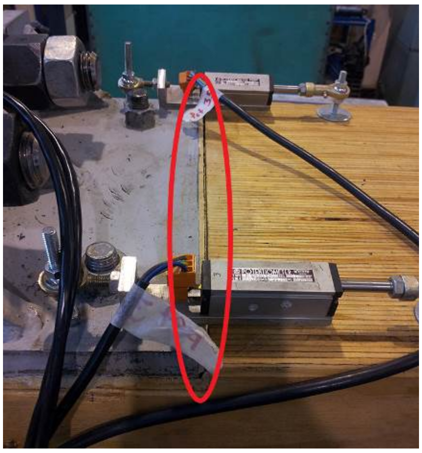


Figure 13. Epoxy separation in beam at dissipater attachment plate

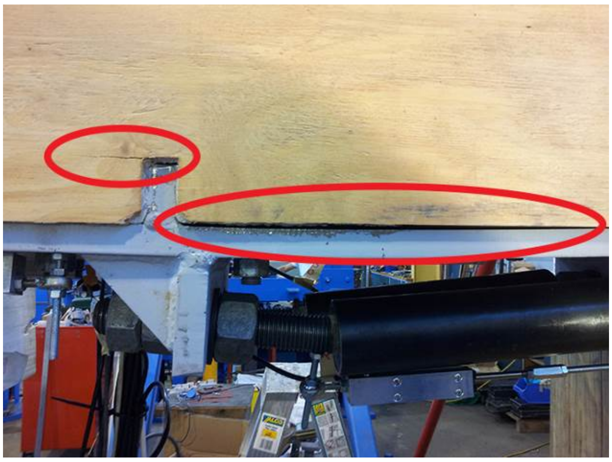


Figure 14. Split in LVL, separation of epoxy and buckling of Necked Rod Dissipater

There was a minor problem with bucking of Necked Plate Dissipaters in one test. At a drift of 3%, the dissipater buckled on one side of the joint as shown in Figure 15 because the anti-buckling block was not connected sufficiently well to the timber. The 80mm screws used to connect this plate were only embedded 30 mm into the wood. Two options were successfully used to remedy this; longer screws, and increasing the size and stiffness of the anti-buckling plate. Even with the buckling shown in Figure 15, the ultimate response of the joint was not significantly affected. As shown in the moment-rotation plot in Figure 10, buckling only occurred on the final cycle to 3.0 % drift and the reduction in moment capacity was less than 5%.

Figure 15. Pull-out of buckling restraint screw in Necked Plate Dissipater

4.4 Reparability

Each of the joints described above was tested twice. This was done to investigate the repairability of the system after a seismic event. Remediation consisted of re-stressing the post-tensioning cables and replacing dissipative elements. No reduction in performance was observed in tests after dissipaters were replaced. Re-stressing was straightforward, using a hand pump and tendon jack. Sufficient experience exists among post-tensioned concrete contractors to make this practical in a commercial setting.

Replacement of the dissipaters was complicated by the permanent elongations after testing. In some cases, the yielded dissipaters had to be cut from the joint. The threaded connections were simplest to replace, however tolerance issues in bolted connections made these more difficult. As oversized holes would not provide enough stiffness, some welding was required to fit replacement dissipaters. The screw connections for Timber Encased Dissipaters are not considered replaceable because of the difficulty of extracting long threaded screws, so supplementary dissipation would need to be installed following a seismic event if required.

5 CONCLUSIONS

This testing has demonstrated several options for designers of Pres-lam beam-column joints. The testing has focused on joint reinforcement and energy dissipation options. These options have been combined to create several options for beam-column joints. All of the tested designs produced stable, well defined moment-rotation relationships, with very good energy dissipation and re-centering behaviour.

Different re-centering performance was targeted for each joint reinforcement option. This was evident in the moment-rotation behaviour produced. For a given target moment capacity, a trade-off between dissipation and re-centering must be made.

Each of the dissipation options performed similarly. The behaviour of the system is almost independent of the type of dissipater chosen. Providing a very high stiffness connection for the dissipaters is critically important for good seismic performance.

Minimal damage occurred during testing. This minor damage did not materially affect the performance of the joints but highlights the need for good detailing. The stiffness of all elements should be considered by designers, especially when detailing connections for dissipation devices.

6 ACKNOWLEDGEMENTS

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