Seismic response of hybrid-LVL coupled walls under quasi-static and pseudo-dynamic testing

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ABSTRACT: Innovative seismic resisting connections for laminated veneer lumber (LVL) timber multi-storey buildings have been recently presented by the authors, based on the combination of unbonded post-tensioning techniques and additional sources of dissipation. As part of an extensive research campaign underway at the University of Canterbury, alternatives solutions for beam-column subassemblies, wall-to-foundation and column-to-foundation connections have been developed, implemented and successfully tested under either quasi-static cyclic and pseudo-dynamic testing regimes. In this paper, the implementation and experimental validation, under both quasi-static cyclic and pseudo-dynamic testing protocols, of post-tensioned/dissipating coupled solid wall systems with different coupling configurations and dissipation devices (i.e. mild steel dissipaters and multi-nailed plywood sheets) is presented. The research investigations confirmed the high seismic performance of these connections and systems, as well as the low-costs and the easy practicality of their implementation on site.

1 INTRODUCTION

Improvements in seismic design philosophies, which refer to damage-control design approaches, have been proposed in parallel with the development of innovative seismic resistant systems. In particular, jointed ductile connections for precast concrete structures (Priestley 1991, 1996, Priestley et al., 1999, Pampanin, 2006) have been implemented and validated. These solutions rely on a discrete dissipative mechanism in selected critical sections guaranteeing the integrity of the whole system.

A particularly effective solution, referred to as a hybrid system, was developed in the U.S.-PRESSS program (PREcast Seismic Structural System), coordinated by the University of California, San Diego, for frame and wall systems; it combines the use of unbonded post-tensioned tendons with grouted longitudinal mild steel bars or dissipation devices (Figure 1a). While the post-tensioning provides a desirable re-centering characteristic the dissipation devices (i.e. mild steel bars) allow adequate energy release from the system.

During the lateral sway mechanism, a dissipative controlled rocking motion occurs at the beam-to-column (Figure 1b), column-to-foundation or wall-to-foundation connections. This peculiar mechanism is characterised by a so-called flag-shaped hysteresis behaviour displayed in Figure 1c.

During the design process of hybrid connections, an opportune calibration of the ratio, named $\lambda$, in a range of 1.2-1.5, between the strength contribution provided by the unbonded post-tensioned tendons and the strength contribution provided by the dissipation devices, assures negligible residual displacements and adequate energy dissipation in order to control the maximum displacement demand. The damage is reduced to minimum acceptable levels, with simple replacement of the dissipation devices, while the structural elements maintain their integrity during a seismic event.

The hybrid solutions, as well as the above mentioned jointed ductile solutions are material independent and similar solutions have been proposed for steel moment-resisting frames (Christopoulos et al. 2001). It has therefore been proposed to extend these solutions for low rise multi-
storey timber construction. Preliminary tests on LVL hybrid (Laminated Veneer Lumber) beam-column subassemblies carried out by Palermo et al. (2005) proved to be very successful and to represent a viable option for multi-storey timber buildings.

The present work, after a preliminary overview on previous beam-to-column and wall-to-foundation tests, covers experimental testing (quasi-static and pseudo-dynamic) carried out at the University of Canterbury involving controlled rocking of coupled-wall systems with pure post-tensioned and hybrid solutions. Different types of dissipaters have been implemented and validated for the hybrid solutions.

Figure 1: a) Hybrid connection (Priestly et al. 1999); b) rocking motion mechanism (courtesy of S. Nakaki); c) idealised flag-shaped hysteresis behaviour.

2 DEVELOPMENT OF LAMINATED VENEER LUMBER (LVL) HYBRID SYSTEMS

An extensive experimental campaign has been carried out on beam-to-column, column-to-foundation and wall-to-foundation subassemblies for the implementation of Laminated Veneer Lumber hybrid solutions. Internal dissipation devices, i.e. steel rods epoxied internally to the member, or external dissipation devices (i.e. fused bars encased in steel tubes, for exterior beam-to-column subassemblies) and column-to-foundation joints (Palermo et al. 2005) have been proposed and tested. The results in terms of force-drift for an exterior beam-column subassembly, within four different arrangements (Figure 2), have confirmed the enhanced seismic performance of the hybrid solutions, where high drift ductility levels were achieved and no residual deformations were observed.

Figure 2: Hybrid beam-to-column test results with a) internal dissipation and b) external dissipation (Palermo et al. 2006)
Moreover, very stable flag-shape hysteresis behaviours were obtained, as expected, with negligible stiffness degradation for both hybrid solutions with internal dissipaters (Figure 2a, HY1, HY2) and external dissipaters (Figure 2b, HY3, HY4).

2.1 Development of solid LVL shear wall solution with externally attached dissipaters

Further to the research carried out on the solid LVL shear walls within internal dissipation devices (Palermo et al. 2006), experimental quasi-static cyclic tests have been carried out on single wall-to-foundation specimens within a cantilever configuration and with externally attached dissipation devices; excellent results have been achieved as shown in Figures 3a, 3b. The four 8mm diameter dissipaters, within unbonded length of 200mm, shown in Figure 3a, consist of steel reinforcing fused bars grouted and encased in steel tubes, which are fixed to external steel plates screwed onto the wall face; while for the self-centering contribution two unbonded post-tensioned tendons with an initial prestressing force of $f_p=30\% f_{py}$ are used.

![Figure 3: Hybrid wall-to-foundation test with external 8mm diameter dissipaters: a) performance of the specimen at 2.5% drift; b) lateral force vs. drift.](image)

A clear “flag shaped” hysteretic loop is observed in Figure 3b with less than 3mm residual displacement, confirming the self-centering characteristics of the hybrid systems. The equivalent yielding point (0.5% drift) corresponds to the actual yielding of the dissipation devices, while the total moment capacity of the system increases with the increasing drift levels due to the elongation of the tendons. No degradation of stiffness and no structural damage are observed and a maximum drift level of 2.5% drift is achieved during the test.

3 EXPERIMENTAL INVESTIGATION ON COUPLED WALL SUBASSEMBLIES

This paper presents the preliminary results of experiments on coupled wall systems under quasi static cyclic and pseudo-dynamic testing. Pure unbonded post-tensioned hybrid solutions with different arrangements and dissipation devices are herein presented as enhanced alternatives to traditional ply-wood timber walls.

Ply-wood shear walls act like deep beams where lateral shear capacity is guaranteed by the panel sheathing and connection to the chords; the bending is resisted by the lateral chords in tension and compression. As shown in Figure 4a, during lateral loading, tension occurs at the base of the wall and appropriate steel devices have to be used to hold the wall down to the foundation. Typical pinching phenomena can be observed in the hysteretic behaviour on the nailed connections joining the panels to the framing. As a result, a reduction of stiffness as well as of energy dissipation occurs, leading to high displacement demand (Deam 1997). These hysteresis loops are similar to those achieved in structural beam-column multiple-nailed connections (Buchanan & Fairweather 1993), (Figure 4b).
3.1 Test set-up, reinforcement and material details

The setup for the testing schedule is shown in Figure 5. The walls are 2.46m high, 0.78m wide and 0.195m thick. They are loaded at a height of 2m above the foundation. The wall is constructed from three sheets of LVL 65mm thick. The sheets are epoxied together and then nailed to hold them in place while the epoxy sets. The material properties based on specific material testing results are shown in Table 1.

Table 1: material properties of system components

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated Veneer Lumber (LVL)</td>
<td>Compressive strength</td>
<td>12 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elastic modulus parallel to the grain</td>
<td>13.2 GPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elastic modulus perpendicular to the grain</td>
<td>6.6 GPa</td>
<td></td>
</tr>
<tr>
<td>Post Tensioning</td>
<td>Yield strength</td>
<td>1530 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ultimate strength</td>
<td>1860 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elastic Modulus</td>
<td>200 GPa</td>
<td></td>
</tr>
<tr>
<td>Mild Steel Dissipaters</td>
<td>Yield strength</td>
<td>340 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield Strain</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elastic modulus</td>
<td>200 GPa</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: a) force transfer in a traditional plywood shear wall (Beattie et al. 2001); b) multiple-nailed beam-column connection.

Figure 5: Test set-up of coupled wall system
Two unbonded post-tensioned tendons for each wall are used to guarantee re-centering capacity. An initial value of 43.5kN (30% of the tendon’s yield force) of the post-tensioning force is adopted.

3.2 Experimental results for quasi-static testing

A series of two cycles of inter-storey drift was applied at increasing levels through the horizontal hydraulic actuator to the cantilevered coupled wall subassembly. The loading protocol is based on ACI T1.1-01, ACI T1.1R-01 (2001) for the testing on innovative jointed precast concrete frame systems.

3.2.1 Unbonded Post-Tensioned Solutions

A pure unbonded post-tensioned solution (i.e. the lower-bound case with no energy dissipation devices for a hybrid system) was tested. Figure 6 shows the recorded values of lateral force vs. drift. A typical non-linear elastic behaviour is represented. The test was stopped at a maximum of 2.5% drift level to prevent the unbonded post-tensioned tendons from yielding in order to preserve the tendons for the further tests.

![Figure 6: Force vs. drift results for pure unbonded post-tensioned coupled walls](image)

The hysteresis lateral force-drift curve shows non linear behaviour with a “knee-point” (equivalent “yielding”), which is due to geometrical non-linearity (i.e. a sudden relocation of the neutral axis position at the critical rocking section). The stiffness after the “yielding” point corresponds to an increase in moment capacity due to the elongation in the tendons. As anticipated no visible damage was observed.

3.2.2 Hybrid solution with external central base attachment of fuse-type dissipaters

The same test set-up, loading protocol and arrangement of the pure unbonded post-tensioned solution was adopted. The four additional dissipaters, located externally in the center of each wall, consisted of longitudinal threaded steel rods machined down to 8mm diameter over a 200mm unbonded length; hollow steel tubes were placed over the fuse length and filled with epoxy to ensure that the device (fuse) did not buckle during the compression cycles. The appropriate design of the dissipater’s length allowed control of the yielding point of the hybrid connection and ensured the maximum design drift with the required displacement ductility. Premature failure of a dissipater during a test dramatically reduces the overall performance of the system; therefore it is desirable that this does not occur.

The perfect efficiency of the dissipation devices during the testing (i.e. no slip of the extremities of the dissipater with the LVL wall) was ensured by mounting plates, fixed to external steel plates attached to the LVL walls using Tek-screws. Moreover, the calibration of the $\lambda$ ratio, between the energy dissipation moment contribution and self-centering moment contribution, guaranteed typical flag-shape behaviour, as shown in Figure 7.

As expected the results for this test were similar to that of the single wall test since the two walls work independently during the loading regime. The yielding point of the force vs. drift curve differs from
that of the single wall system (section 2.1) due to the different placement of the dissipaters (i.e. center base located for coupled walls and edge base located for single walls). This method of dissipating connection does not rely on the relative displacement between the two walls and therefore is independent of the distance between the walls.

3.2.3 Hybrid solution with external attachment of plywood sheet dissipaters

The alternative method of dissipation herein presented is two 9mm sheets of plywood placed against the faces of the two walls and nailed around the perimeter of the plywood sheet. This sort of dissipater is cheaper than the external fuse-type dissipater; the movement between the walls causes plastic deformation of the nails which provides the energy dissipation contribution to the hybrid system. Overstrength design has been adopted to ensure that the nails are the “weakest element” and that failure of the plywood sheet does not occur. The spacing of the nails was set to ensure that the ratio, $\lambda$, for the system was sufficient to provide enough self-centering and dissipation contribution. Figure 9 shows the results in terms of lateral force-drift for this system configuration.

A reduction in the stiffness occurred during the test due to the stiffness reduction of the nailed plywood dissipaters, leading to less energy dissipation contribution. In spite of the reduced seismic performance, this method of dissipation is cheaper and simpler to attach compared to the aforementioned fuse-type dissipaters.

3.3 Pseudo-dynamic cyclic testing on pure unbonded post tensioned and hybrid solutions

Pseudo-dynamic tests were performed on cantilever coupled wall-to-foundation subassemblies with unbonded post-tensioned-only as well as hybrid solutions, using the same test set-up configuration used for the quasi-static tests. In particular, for the hybrid configuration, the investigation of the seismic performance was limited to the setup with the central external base fuse type dissipater. As the wall is of 2/3 scale assuming constant density, a 2/3 scaling factor was applied to the adopted
accelerogram. Three different earthquake events were used as reported in Table 2.

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Label</th>
<th>Year</th>
<th>Mw</th>
<th>Soil Type</th>
<th>Duration, s</th>
<th>PGA, g (scaled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape Mendocino</td>
<td>Cm1</td>
<td>1992</td>
<td>7.1</td>
<td>C</td>
<td>44</td>
<td>0.441</td>
</tr>
<tr>
<td>Landers</td>
<td>Lan2</td>
<td>1992</td>
<td>7.3</td>
<td>D</td>
<td>44</td>
<td>0.416</td>
</tr>
<tr>
<td>Loma Prieta</td>
<td>lp5</td>
<td>1989</td>
<td>6.9</td>
<td>D</td>
<td>39.6</td>
<td>0.363</td>
</tr>
</tbody>
</table>

As part of the required information, an equivalent mass of 148.15 kN s²/m was assumed. This corresponds to the expected gravity loading on the wall within a single storey timber building. An equivalent damping of 5% was also assumed. These data assumptions allow the solution of the equation of motion for the single degree of freedom system within the pseudo-dynamic algorithm. The stiffness value is calculated incrementally by the program. Figure 10 shows the results in terms of lateral force-drift for the three abovementioned accelerograms for both the pure unbonded post-tensioned and hybrid systems.

As expected, the results obtained are very similar to those from the quasi-static testing. The three accelerograms produced different displacement/drift demand. It is evident that the hybrid solution allows the reduction of the maximum drift demand with respect to the pure unbonded post-tensioned solution with the dissipaters providing the additional dissipation capacity. For both the solutions negligible residual drift/displacements are guaranteed.

4 CONCLUSIONS

The experimental results of cyclic quasi-static tests on the presented coupled wall-to-foundation systems further confirmed the enhanced performance of hybrid jointed ductile connections compared to traditional systems. The great design flexibility of hybrid solutions is confirmed by the different arrangements investigated. The negligible residual displacements achieved and the integrity of the system (no damage in the gravity load supporting elements) guarantee reduced post event rehabilitation costs.
Moreover, with the dissipation devices being the only sacrificial elements of the hybrid connection, the repair cost is limited to the replacement of the dissipaters. The experimental tests confirmed the good performance of the external longitudinal mild steel dissipaters (no degradation of stiffness) while for the plywood sheet dissipation mechanism further investigations and developments are still required.

Other hybrid solutions, not herein presented, with internal dissipaters located between the coupled walls, have been developed and implemented. The relative movements of the walls activate the dissipaters which provide the dissipation contribution. This solution, still under refinement, has the clear advantage of being less invasive since the dissipaters are hidden between the walls.

The experimental results confirm the design flexibility and the enhanced performance of the hybrid coupled-walls, which combined with the speed of construction, creates exciting potential for the construction of low-rise multi-storey buildings and becomes a valid alternative to the traditional plywood sheathed timber framed walls.

ACKNOWLEDGEMENTS

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