SEISMIC DESIGN OPTIONS FOR POST-TENSIONED TIMBER WALLS

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ABSTRACT

Structural systems made of prefabricated laminated timber members connected by unbonded post-tensioning and additional mild steel reinforcement have recently been proposed for multi-storey timber buildings. The benefits of the use of post-tensioning to assemble prefabricated timber elements are rapid erection, simple connections, and high seismic resistance. It has been shown that prefabricated post-tensioned timber members can be designed to have excellent seismic resistance, with the post-tensioning providing re-centering capacity after major earthquakes, while energy is dissipated through yielding of replaceable steel elements. Both post-tensioning and energy dissipating elements contribute to the stiffness and strength of the overall system.

Investigation into the seismic response of twin post-tensioned timber walls, uncoupled and coupled, with and without energy dissipaters has been performed as part of a larger research programme on timber structures at the University of Canterbury. The walls were fabricated from laminated veneer lumber (LVL). A number of special fuses all made of mild steel were used as energy dissipating devices. The energy dissipaters are attached externally so that they can be removed and replaced easily after a major earthquake. Under gravity or low-seismic loading they would be able to provide, as per standard mild steel reinforcement, substantial stiffness and strength. As additional option, plywood sheets have been used to couple the LVL walls in which case the nails dissipated energy through yielding during rocking motion of the walls. This paper discusses the experimental tests and numerical validation of the response of post-tensioned timber wall systems. The results show excellent seismic behaviour with very little residual damage. This research also demonstrates the practical feasibility of post-tensioned timber walls for multi-storey timber buildings as well as their versatility of design and use.

1. INTRODUCTION

The potential for acceptance of structural systems with prefabricated members in seismic applications has increased significantly in the last decade due to the introduction of jointed ductile connections in concrete. These high-performance seismic resisting systems, developed under the U.S. PRESSS (PREcast Structural Seismic Systems) programme coordinated by the University of California, San Diego (UCSD) for the seismic design of multi-storey precast concrete buildings, has led to a new design approach for moment-resisting frames and walls [11]. Such solutions are based on dry joints between pre-fabricated elements and unbonded post-tensioning techniques to connect the precast elements. A particularly efficient solution is the "hybrid" system which combines unbonded post-tensioned tendons with more traditional non prestressing steel reinforcement also acting, where needed in a seismic region, as damping/energy dissipating devices [15]. The unbonded post-tensioning provides a re-centering capacity (in addition to the axial load contribution, when present), while the inelastic deformation is concentrated at the critical section which undergoes a "controlled rocking" motion during an earthquake. The dissipation capacity is provided by yielding elements, which can consist of mild steel bars embedded within the members or externally attached to

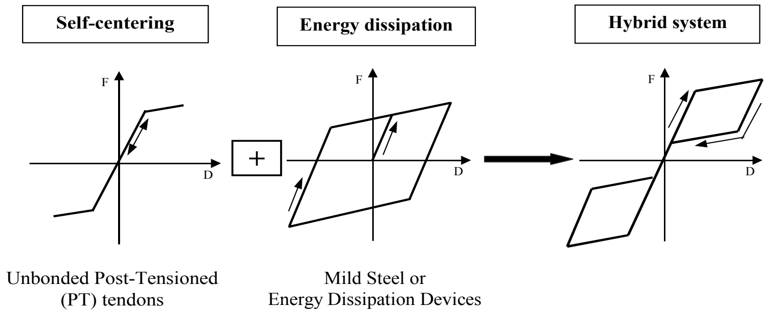


Figure 1. Idealized flag-shape hysteresis loop (NZS3101:2006).

the members. The typical behaviour of such systems is characterized by flag-shaped hysteresis behaviour (Figure 1).

As a result, a very efficient structural system is obtained which can undergo large inelastic displacements similar to their traditional counterparts (e.g. monolithic connections in concrete), while limiting the damage to the structural system and assuring full re-centring capacity after the seismic event (thus producing no residual or permanent displacement) subject to ensuring an adequate ratio between axial loads (gravity and post-tensioning) and yielding elements, such as dampers. After the original developments of hybrid solutions in precast concrete structures, the concept was later implemented in timber structures, showing that the PRESSS-technology can be successfully implemented regardless of the properties of the material used [7]. Preliminary tests, carried out by Palermo *et al.* and Smith *et al.* [7,9,13] proved the feasibility of multi-storey timber construction, considering moment-resisting frame systems and individual structural walls.

2. ALTERNATIVE SOLUTIONS FOR STRUCTURAL WALL SYSTEMS

It is well established that structural walls can form efficient lateral load resisting systems in multi-story buildings. The lateral forces produce an overturning moment which is resisted at the base of a single cantilever wall. If the wall is formed by two vertical cantilevers joined by a number of coupling beams, the overall behaviour is that of a frame with the coupling elements acting as members. The overturning moment can thus be counteracted by the coupled axial forces produced in the two cantilever walls. This means that, for a given lateral load, the net required section size of each wall is reduced in the coupled configuration when compared to a single cantilever wall.

It has been accepted that the non-linear response of structural systems can be advantageous in many situations because the members are subject to lower seismic forces and overturning moments and consequently they are more economically designed [3]. As opposed to traditional cantilever walls that involve development of plastic hinges at the base, structural walls made of precast panels utilizing the recently developed hybrid concept develop a rocking motion at the base used to activate energy dissipation elements at the base. Another solution is to use coupling beams with cantilever walls as an additional source of strength as well as energy dissipation through yielding of the coupling beams. As an efficient alternative to the use of coupling beams, coupling links could be used as an additional source of strength and dissipation. While energy dissipation is primarily achieved through yielding of the coupling links throughout the height of the walls (Figure 2), almost the entire wall (except the rocking base) behaves virtually elastically.

Alternative energy dissipation devices can be adopted as coupling systems between closely spaced walls (Figure 2), ranging from ductile shear links to friction devices, and to flexural-yielding elements. In a coupled rocking walls configuration the energy dissipation devices are activated and take advantage of the relative vertical movements between the adjacent walls. Several different arrangements of connectors to couple adjacent precast post-tensioned concrete wall panels were proposed and tested at National Institute of Standards and Testing, USA and within the Five Storey PRESSS Test-Building at UCSD [11,12]. Among different dissipative mechanisms that would be activated by the relative displacement of the adjacent walls during the rocking motion, the U-shaped flexural plates (UFP) showed a particularly stable hysteretic behaviour without evident losses of stiffness or strength at a high level of deformation [4]. Therefore, they have been established as a primary candidate for the development of coupled post-tensioned hybrid wall systems.

This paper also investigates post-tensioned LVL walls coupled with plywood sheets. Plywood sheathing is common in typical seismic-resisting systems adopted for multi-storey timber construction. Strength and ductility are provided by the deformation of nails holding the plywood to the studs and plates. During movements of walls due to cyclic lateral loading the nailed plywood-LVL wall connection produces typical pinched hysteresis loops with progressively reduced stiffness and larger displacements. The tendons provide re-centering capacity in post-tensioned walls, ensuring almost negligible residual displacements. Another advantage of externally attached plywood sheets is the ease of replacement or repair after an earthquake and the accessibility for maintenance during the life-time of the building.

3. DETAILS OF LVL WALL TEST SPECIMENS

Three LVL wall specimens were tested in this study. The post-tensioned-only specimen (PT) was tested at an initial post-tensioning level of 30% of yield stress of the

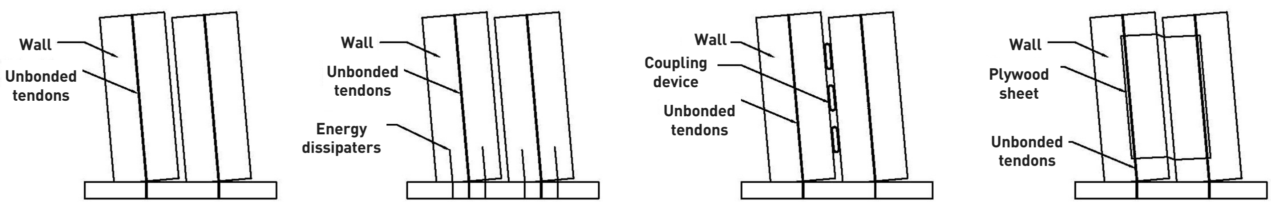


Figure 2. Post-tensioned rocking walls, post-tensioned hybrid walls and post-tensioned coupled walls.

Table 1. Details of specimens tested.

Specimen	Type	Initial PT	Energy Dissipaters
PT	PT-only	43.5kN	None
HY	Hybrid with Axial Dissipaters	43.5kN	4-8mm f
HU	Hybrid with UFP	43.5kN	4-5mmx100mm
HP	Hybrid with Plywood Sheets	43.5kN	2-1500x1000 x12mm

tendons (f_{pty}@1570 MPa). The hybrid specimen with axial dissipaters is designated with HY. The hybrid specimen HU had two pairs of UFP with plates of 5 mm thickness and 100 mm width. In hybrid specimen HP the walls were coupled with two 12 mm thick plywood sheets attached to the walls with nails spaced at 100 mm centre to centre. Like the post-tensioned only specimen, all the hybrid specimens were tested with an initial prestressing level of 30% of yield stress.

The LVL specimen wall was constructed on a 2/3 scale. The properties were accordingly scaled assuming the density as a constant. Each wall was 2.5 m in height, 0.78 m wide and 0.195 m deep. The walls were loaded at 2 m height from the foundation. The width and the depth were scaled down from dimensions of standard dimensions of LVL blocks with 1.2 m width. The solid LVL walls were constructed from Hyspan® LVL. Three layers of blocks, each with 0.063 m thickness, were laminated to make up the 0.195 m thickness of each wall. In each wall, four panels (2.5 m high, 0.1 m wide and 0.063 m deep) where sandwiched between two solid sheets (2.5 m high, 0.78 m wide and 0.063 m deep) with an epoxy resin to create three ducts (0.12 m wide and 0.063 m deep) running along the length of the wall. The post tensioning cables (seven wire strands, A_{pt}=99 mm^2) were placed at the centres of the two outer ducts.

A steel base was constructed to provide a strong smooth surface which was used to carry out the tests without damage to the strong floor of the laboratory. Use of the steel base permitted easy addition and removal of dissipater connections and shear key devices, as well as the connection of the tendons. Although it did not represent the foundation used in common practice, it was nevertheless an economical and time-efficient option for a large number of tests to be carried out.

4. EXPERIMENTAL TESTING OF LVL WALLS

The setup of the coupled walls is shown in Figure 3. The same specimen has been used for all the tests presented in this work. The material properties are given in Table 2 based on specific material testing. Four unbonded post-tensioned tendons (seven wire strands, 12.7 mm diameter), two per wall, were stressed to an initial force of 43.5 kN. The low design value was decided upon to prevent possible yielding of the tendons. Due to the particular geometric configuration and location of the tendons, small increments of gap opening produced marked increase in forces in the tendons.

Both quasi-static cyclic and pseudo-dynamic testing were carried out. The loading protocol adopted for quasi-static cyclic testing was a modification of ACI T1.1-01 and ACI T1.1R-01, proposed for the testing on innovative jointed precast concrete frame systems [1]. The modification maintained the target drift levels, but reduces the number of cycles, from three to two cycles, for each level of displacement.

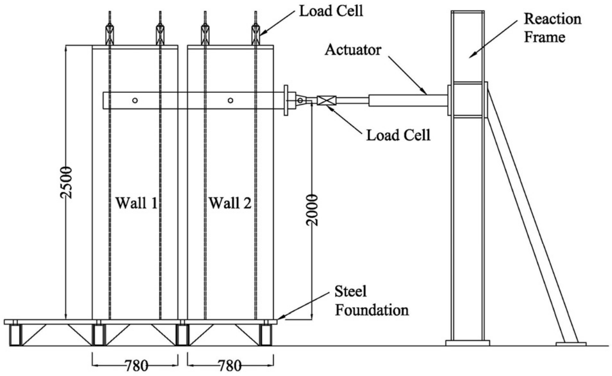


Figure 3. General test setup of walls (dimensions in mm).

Table 2. Material properties of system components.

Laminated Veneer Lumber (LVL)	Compressive strength parallel to the grain	45.0 MPa
	Compressive strength perpendicular to the grain	12.0 MPa
	Elastic modulus parallel to the grain	13.2 GPa
	Elastic modulus perpendicular to the grain	0.66 GPa
Post Tensioning	Yield strength	1560 MPa
	Ultimate strength	1860 MPa
	Elastic modulus	200 GPa
Mild Steel Dissipaters	Yield strength	340 MPa
	Yield strain	0.0015
	Elastic modulus	200 GPa

Pseudo-dynamic tests were performed to simulate the dynamic response of the structural system subjected to an earthquake input ground motion and appreciate the effect of hysteretic damping and re-centering properties on the overall response (maximum and residual displacements). The same test set-up as the quasi-static testing was adopted. As the walls were of 2/3rd scale, assuming constant density criterion, an amplification of 3/2nd was applied to the accelerations while the duration (time) was reduced by 2/3rd. Details of the adopted earthquake record, which is compatible with the response spectra for the New Zealand Standard for a return period of 100 years, are shown in Table 3. For the hybrid walls the ground motions were scaled up to 150% which represent a return period of 500 years. An equivalent mass of 148 kN s2/m has been assumed, corresponding to the expected gravity loading of the wall within a single storey timber building. An equivalent viscous damping of 5% (initial stiffness proportional) was assumed in the pseudo-dynamic algorithm.

Table 3. Characteristics of the adopted earthquake events.

Event	Year	M_w	Soil type	Duration (sec)	PGA, g (scaled)
Landers	1992	7.3	D	44.0	0.334

5. QUASI-STATIC EXPERIMENTAL RESULTS

Results of quasi-static tests of the two arrangements tested are presented in Figure 4. The typical "Non Linear Elastic" and "Flag Shape" hysteresis loops with full recentering capacity were observed in the unbonded post-tensioned only and hybrid solutions respectively. The change of the hysteretic behaviour due to the use of axial dissipaters can be seen clearly in Figure 4a. In Figure 4b the force-displacement curve is that of a coupled wall system with 4-5 mm thick UFP, compared with the system without UFP and tested separately. The results of the walls with the two different energy dissipation systems show almost the same behaviour and roughly the same amount of energy dissipation. There is a small amount of residual deformation in the case of the walls with UFP because of sliding at the bases of the walls.

The recentering capacity of this type of systems is measured by the parameter λ which is the ratio between the recentering moment and the moment provided by the energy dissipation elements. In this case the three systems with axial dissipaters, UFP and plywood have comparable values of the parameter λ.

6. PSEUDO-DYNAMIC EXPERIMENTAL RESULTS

Figures 5 and 6 show the displacement responses of different specimens during the pseudo-dynamic testing under the two earthquake records, comparing the

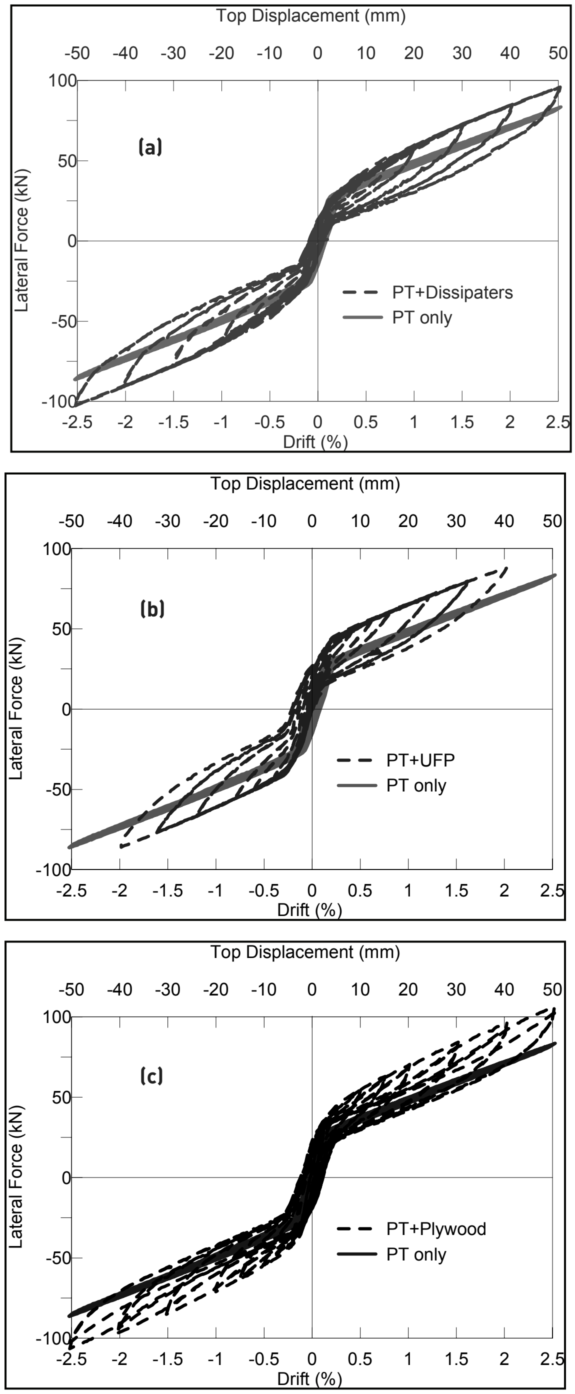
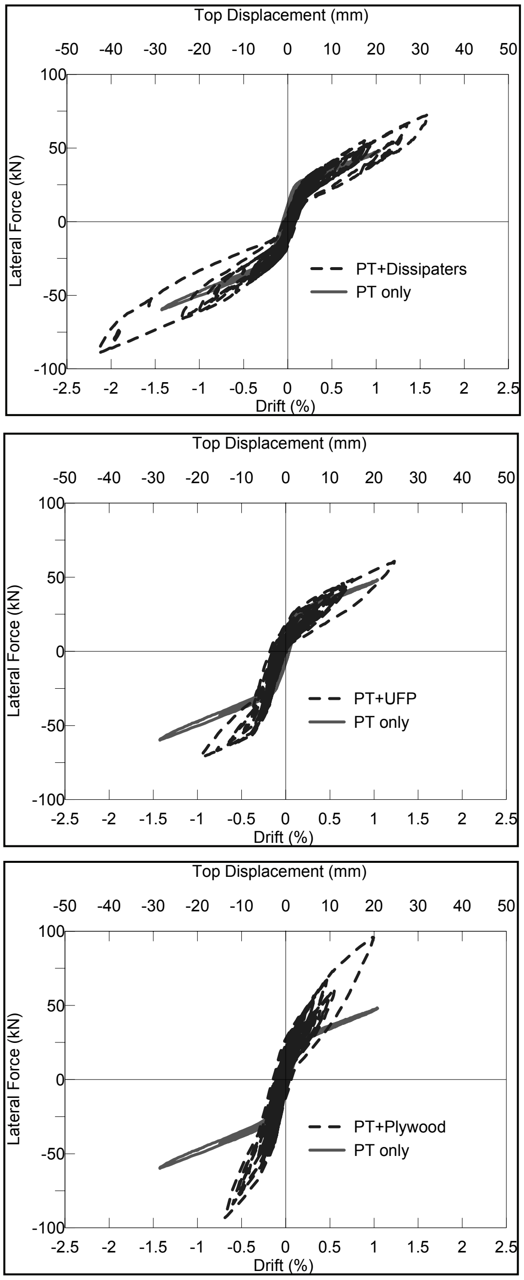


Figure 4. Force-displacement plots of Specimens HY (a), HU (b) and HP (c) compared to Specimen PT.

results of the hybrid solutions with that of the post-tensioned only solution. As expected the hybrid solutions result shows wider hysteretic loops when compared with the post-tensioning-only solution due to the additional energy dissipation provided by the axial dissipaters, UFP and plywood. There is a noticeable increase in post elastic stiffness of the plywood walls compared to the quasi-static test indicating dynamic readjustments within the connections. As typical of the flag-shape hysteresis behaviour, no significant residual deformations were observed despite the irregular and asymmetric nature of the response.



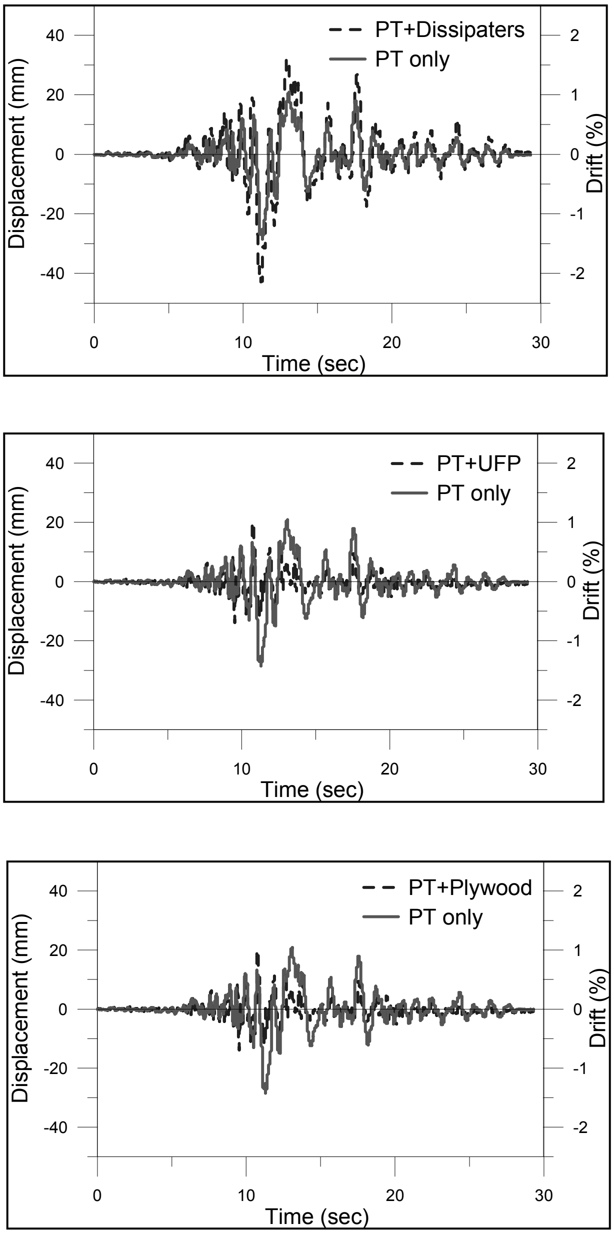


Figure 5. Pseudo-dynamic plots of Specimens HY, HU and HP (top to bottom) compared to Specimen PT.

Figure 6. Time-history plots of top wall displacement for Specimens HY, HU and HP (top to bottom) compared to Specimen PT.

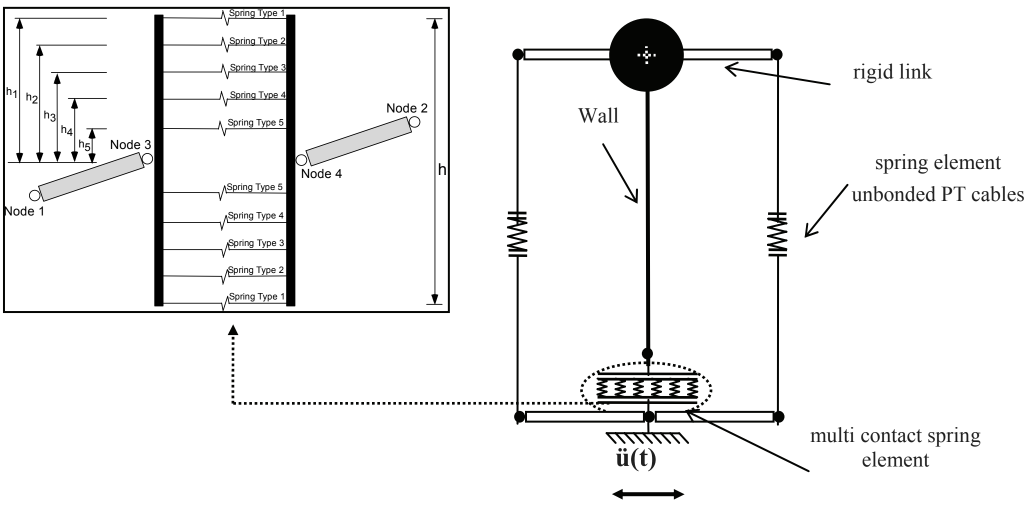


Figure 7. Schematic of multi spring model of wall.

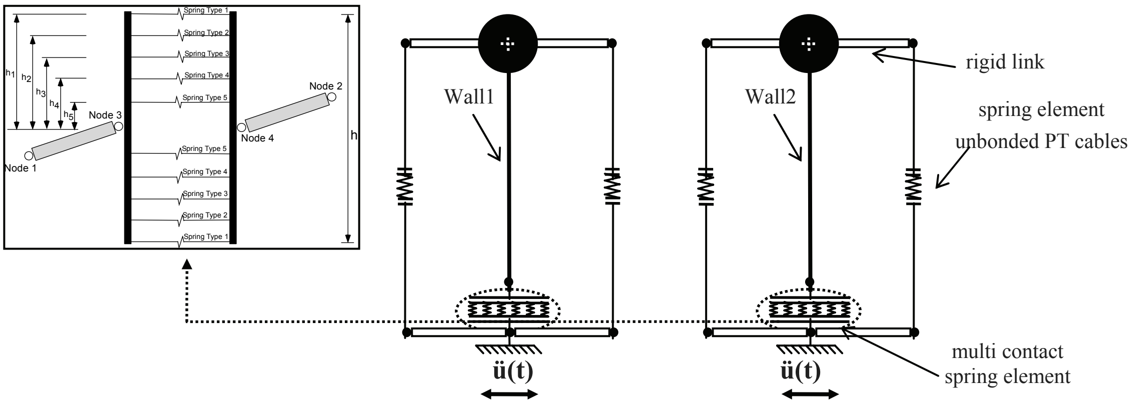


Figure 8. Schematic of multi spring model of coupled walls.

7. NUMERICAL MODELS

A numerical model of the coupled walls subassembly, based on a section analysis and lumped plasticity approach, was prepared and validated on the experimental results.

The moment-rotation behaviour of the walls was calculated based on the analytical procedure referred to as Monolithic Beam Analogy, MBA, for jointed ductile connections originally proposed by Pampanin *et al.* (2001) and subsequently refined by Palermo (2004), which relies on a member compatibility condition in terms of displacements between a monolithic and a hybrid solution [9,10]. The combined contributions from the prestressing tendons and the energy dissipaters in a hybrid connection are modelled by two elements in parallel with appropriate characteristics to produce the flag-shaped hysteresis.

The model is characterised by representation of contact in the critical section (wall-to-foundation) with a multi-spring element [2,8,14]. The multi-spring model can well simulate the contact section interface via a number of axial springs. The model achieves a good simulation of the local stresses, strains and variation of the neutral axis position at the joint opening and allows for the beam elongation effect. The characteristics of the springs can be properly chosen considering the different contact (unilateral, bilateral) behaviour of the section. The other elements characterising the hybrid connection (i.e. the unbonded post-tensioned cables and the external/internal energy dissipators with unbonded length) are modelled with longitudinal springs, pretensioned in the case of the unbonded PT cables. The hysteretic rule for the unbonded PT cable can be assumed non-linear elastic, if the cables do not reach the yielding point, while for the energy dissipators a proper hysteretic model has to be chosen depending on the type of energy dissipator. For the axial dissipaters, the Dodd-Restrepo model was used while the UFP was represented by the Al-Bermani hysteretic rule. The wall is represented by an elastic beam element. Figures 7 and 8 show the schematic multi-spring model of the hybrid specimen with axial dissipaters and hybrid coupled walls, respectively. The model of the post-tension only specimen is the same as that for the hybrid specimen with axial dissipater, without the springs at the base representing the energy dissipaters.

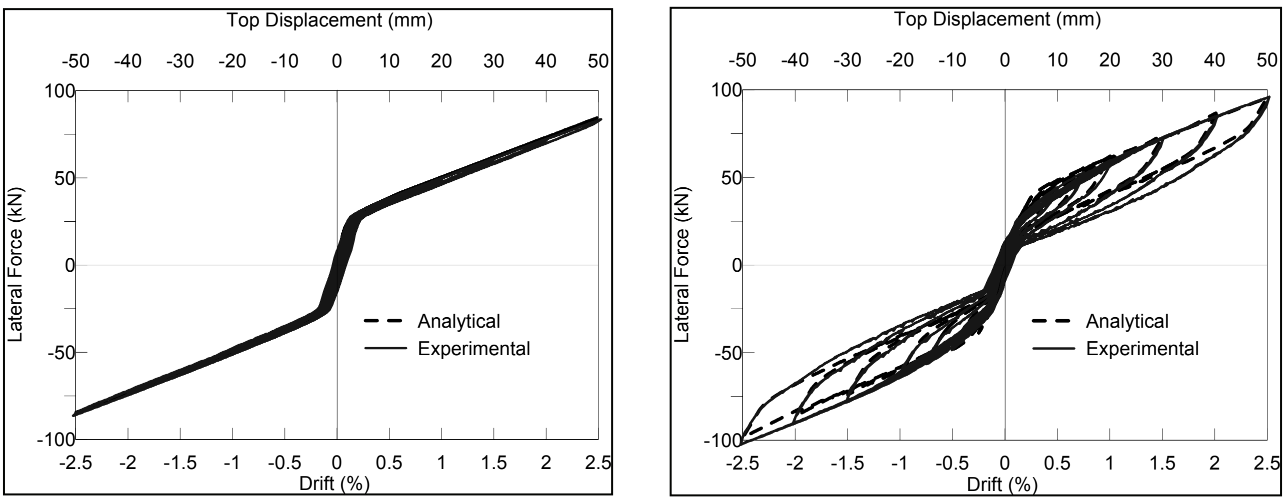


Figure 9. Force-displacement comparisons of Specimens PT (left) and HY (right).

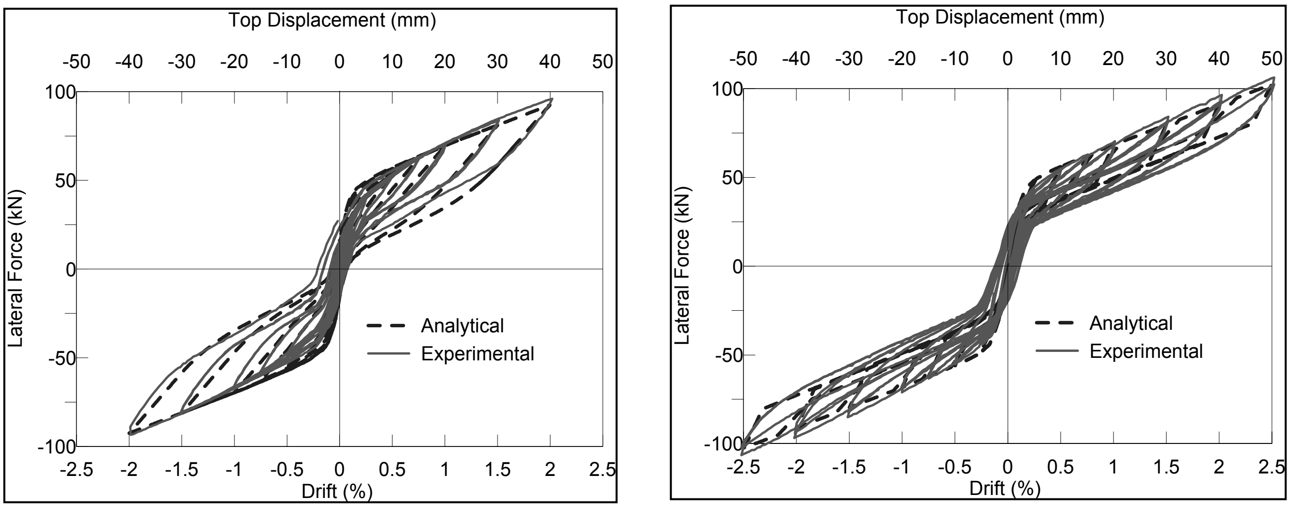


Figure 10. Force-displacement comparisons of Specimens HU (left) and HP (right).

8. COMPARISON WITH EXPERIMENTAL RESULTS

The analytical-quasi-static experimental comparison of the response of the walls is shown in Figures 9 and 10. The adopted numerical model provided satisfactory representation of the behaviour of the post-tension only walls, walls with axial dissipaters, UFP devices and plywood sheets.

CONCLUSIONS

The efficiency of using mild-steel axial and U-shaped hysteretic dampers with post-tensioned LVL walls has been presented. Significant energy dissipation as well as excellent re-centering was achieved in all the experiments. Preliminary results of the experimental investigation confirmed the enhanced performance of such hybrid timber systems. The configuration of the U-shaped plates, developed in the 1970s and now recognised as one of the preferred dissipater systems for coupled rocking walls, allows the rocking behaviour of wall systems to be translated into an efficient energy dissipation mechanism. The hysteretic behaviour is very stable and predictable and the manufacturing of the dissipaters or the UFPs is easy and economical. Virtually no damage is observed in the structural members after many cycles of seismic loading, which ensures low cost for post-earthquake repairs. The repair costs of the system, after a major earthquake, consist of the possible (most often not required) replacement of the only sacrificial elements, i.e. the axial dissipaters or the UFPs, which is a low-cost operation. For the plywood sheets, similar cheap and simple repair methods such as addition of new nails can be taken up if necessary after yielding of a significant number of the original nails. The energy dissipation characteristics of the axial dissipaters, the UFPs and the plywood sheets highlights significant design flexibility of the hybrid systems. The proposed arrangements have the potential to be valuable options for achieving excellent seismic resistance in multi-storey timber buildings.

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