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CODE PROVISIONS FOR SEISMIC DESIGN OF MULTI-STOREY POST-TENSIONED TIMBER BUILDINGS

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1 Introduction

Recent developments and successful preliminary experimental validations of innovative types of ductile connections for multi-storey seismic-resisting laminated veneer lumber (LVL) timber buildings have opened major opportunities for extensive use of structural timber in seismic regions. These particular solutions, named *jointed ductile connections* or *hybrid systems* are based on post-tensioning techniques to assemble structural LVL members for both frame and shear wall systems which are designed to exhibit controlled rocking deformations during seismic loading. These systems have been proposed and successfully tested using concepts developed for high-performance seismic-resisting precast concrete buildings, currently being approved in major seismic codes and design guidelines worldwide. The extremely satisfactory results of quasi-static cyclic and pseudo-dynamic experimental tests on exterior beam-column joint subassemblies, column-to-foundation connections and shear wall systems have provided valuable confirmation of the high seismic performance of these LVL systems, as well as the reliability of the adopted design criteria and methodology. In this paper, after a brief introduction to the concept of post-tensioned seismic-resisting LVL structures and an overview of experimental results, particular focus will be given to seismic design aspects, within a performance-based design approach, as a sound basis for the preparation of seismic design code provisions.

2 Developments in High-Performance Seismic Systems

2.1 Refinements in performance based seismic design approaches

In the last decade, significant development and refinements of performance-based seismic engineering (PBSE) philosophies (SEAOC Vision 2000, 1995) and corresponding compliance criteria, have been driven by the recognized importance of designing ductile structural systems to undergo inelastic cycles during earthquakes while sustaining their integrity and minimizing structural and non-structural damage after the earthquake. Within a typical performance-based design framework, different levels of structural damage and, consequently, repair costs (associated with performance levels related to Operational Conditions, Damage Control, Life Safety and Collapse Prevention) may be expected, depending on the seismic intensity and the importance given to the structural facilities during the design process.

Structural damage is typically accepted as an unavoidable result of inelastic behaviour during an earthquake. Following the common goal of reducing severe socio-economical losses due to earthquake events to an “acceptable” level in seismic-prone countries, an increased focus has been given to the development of design approaches and adequate technology to respect the performance requirements typical of a damage control objective, after having prevented life safety and structural collapse.

Recent developments in performance-based design and assessment (MacRae and Kawashima, 1997, Pampanin et al., 2002 Christopoulos and Pampanin, 2004) have highlighted the limitations and inconsistencies related to current PBSE approaches, and have emphasised the critical role of permanent residual deformations, typically sustained by a structure after a seismic event even when “well designed” according to current codes. Residual damage is a major additional and complementary damage indicator to those typically adopted, i.e. inter storey drift, ductility and/or cumulative energy. Considering the impact of residual deformations on the cost of repairing and expected downtime (including the difficulty of straightening a building to its original position) after an earthquake event, seismic resisting systems or devices with re-centering properties naturally attract favourable attention.

2.2 Traditional solutions for seismic resisting ductile systems

Regardless of the structural material adopted (i.e. concrete, steel, timber), traditional solutions to achieve adequate global and local ductile structural behaviour rely on the inelastic behaviour of the material, allowing for plastic deformations to occur within selected discrete and sacrificial regions (typically referred to as “plastic hinge regions”), designed according to capacity design principles in order to protect the whole system from undesired inelastic mechanisms.

Alternatively, seismic protection can rely on the use of energy dissipation and supplemental damping devices (including base isolation), designed with passive, active or semi-active control to protect the main structural skeleton from inelastic mechanisms and damage.

In timber engineering, several alternative solutions have been studied and developed in literature to provide moment-resisting connections in timber construction, for both lateral load resisting wall or frame systems. Feasibility studies of multi-storey timber buildings have been described by Halliday & Buchanan (1993) and Thomas et al. (1993). Depending on the type of connection and structural details, many alternative arrangements are available ranging from mechanically fastened solutions with nailed, bolted or dowel connections to glued or epoxied steel rods. These solutions apply to solid sawn timber in large sizes, glue laminated timber (glulam), or LVL. Significantly different forms of inelastic behaviour can occur, leading to different levels of ductility capacity and hence different overall structural performance. Typical pinching phenomena can be observed in the hysteresis behaviour of nailed or steel rod connections (Fig. 1a) which leads to a reduction of stiffness (both loading and unloading) as well as a reduction of energy dissipation capacity, hence higher displacement demand (thus damage) than in well designed steel or concrete structures. These hysteresis loops are similar to those achieved in structural walls with nailed plywood sheathing (Deam 1997).

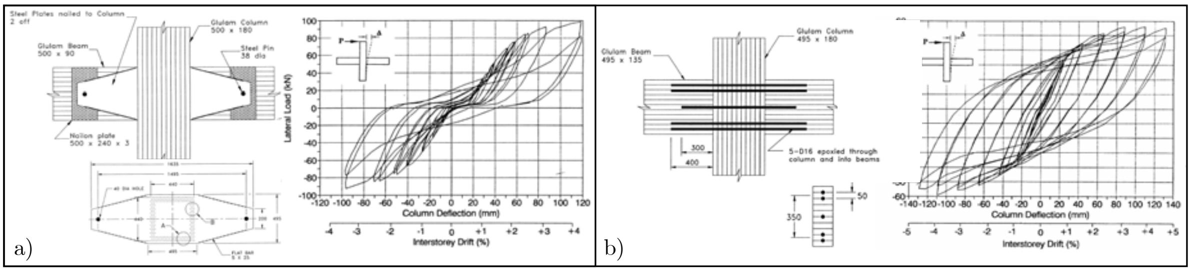


Figure 1. Layout and hysteresis loops for glulam frame systems: a) multiple-nailed connection; b) epoxied rods (Buchanan & Fairweather, 1993).

An overview of seismic resisting solutions for multi-storey glulam timber buildings (Buchanan & Fairweather, 1993) proposed alternative arrangements for steel epoxied connections with or without additional sacrificial steel brackets to accommodate the inelastic behaviour. In particular the simplest version of the connection (Fig. 1b) showed satisfactory behaviour under cyclic loading, similar to the behaviour of a properly designed plastic hinge in reinforced concrete members, with stable dissipating hysteresis loops and limited stiffness degradation. However, in line with the previous discussion on performance based design requirements, excessive permanent residual deformations would be expected after an earthquake event, as in typical monolithic concrete or steel structures.

2.3 Jointed ductile connections: damage-resistant, self-centering and dissipative systems

Recent developments in precast concrete moment-resisting frames or interconnected shear walls (Priestley 1996, Priestley et al., 1999) (Fig. 2a), under the U.S. PRESSS (PREcast Seismic Structural System) program as well as subsequently in steel moment-resisting frames (Christopoulos et al., 2002b), (Fig. 2b), have resulted in the revolutionary development of high-performance, cost-effective, seismic resisting systems which can undergo inelastic displacements similar to their traditional counterparts, while limiting the structural damage and assuring full re-centering capability. These innovative solutions, typically referred to as *jointed ductile connections*, differ from monolithic solutions (i.e. cast-in-place reinforced or precast concrete; welded or bolted connections in steel) in that prefabricated structural elements are connected by using unbonded post-tensioning, the inelastic demand is accommodated within the connection through opening and closing of an existing gap, while the structural elements are kept in the elastic range with a very limited level of damage. These connections can be located at the beam-column, column-foundation or wall-foundation interface. A particularly efficient solution is provided by the *hybrid* system (Fig. 2a) where an adequate combination of self-centering capacity (unbonded tendons plus axial load) and energy dissipation (mild steel or other dissipation devices) leads to a sort of controlled rocking motion defined by a peculiar “flag-shaped” hysteresis loop (Fig. 2c).

Extensive numerical and analytical studies have recently focused on further refinement of these systems, and development of simple and reliable modelling and design procedures. Several on-site applications adopting PRESSS-type technology have been implemented in seismic countries around the world including U.S., Europe, South America, Japan, and New Zealand. Major seismic codes or design guidelines (*fib* Bulletin *27* 2004, EC8, Architectural Institute of Japan (AIJ), ACI T1.2-03 2003, NZS3101:2006) have incorporated the possibility of using similar solutions, typically referred to as *jointed ductile connections* or *connections with concentrated ductility*. An overview of recent developments of hybrid solutions in precast concrete construction including research outcomes, modelling and design aspects, code provisions and guidelines as well as practical applications can be found in Pampanin (2005).

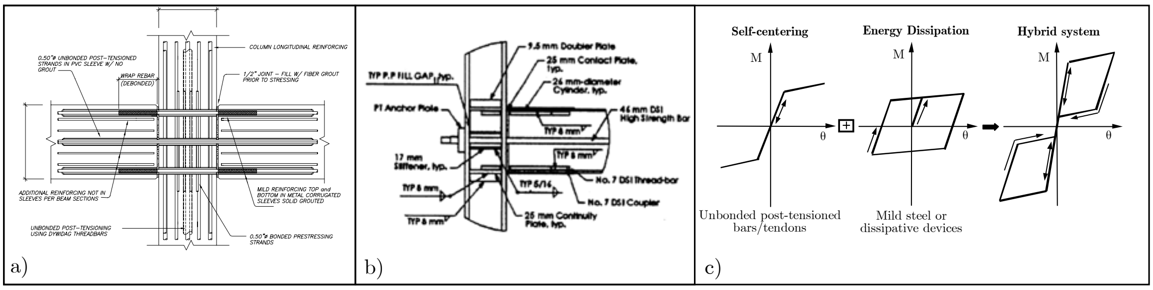


Figure 2. Hybrid solutions: a) for precast concrete frame systems (PRESSS program, Priestley et al., 1999); b) for steel moment resisting frames (Post-Tensioned Energy Dissipation, PTED, Christopoulos et al. 2002b); c) idealised flag shape hysteresis loop.

3. Extension of the Hybrid System Concept to LVL Seismic-Resisting Multi-Storey Buildings

In recent contributions from the authors (Palermo et al., 2005, 2006) the concept of hybrid or controlled rocking systems has been proposed for multi-storey timber seismic-resistant structures with particular emphasis on Laminated Veneer Lumber (LVL).

As a structural material, LVL is a superior alternative to sawn timber or glulam because the 3 mm thick veneers are specially selected, then staggered during processing so that the selected wood material is thoroughly mixed and the defects, such as knots, are randomised to a point where their influence on the material properties can be assumed negligible. Due to the higher homogeneity, the tension strength of LVL can reach values at least 3 times that of sawn timber from the same population of trees. However it is worth underlining that the hybrid connection (Fig. 3) is not significantly affected by the strength of the material, provided that proper confinement is given to the compression area to avoid crushing of the edge layers, hence this connection can be used with different wood-based materials (i.e., sawn timber, glulam etc).

Figure 3 shows a conceptual hybrid solution for LVL beam-column connections based on the combination of post-tensioning and internal dissipaters (e.g. epoxied mild steel bars). In the following paragraphs, an overview of the connection mechanism and design philosophy will be given, supported by the very satisfactory results of experimental validation on prototype connections for beam column joints, cantilever columns and wall systems.

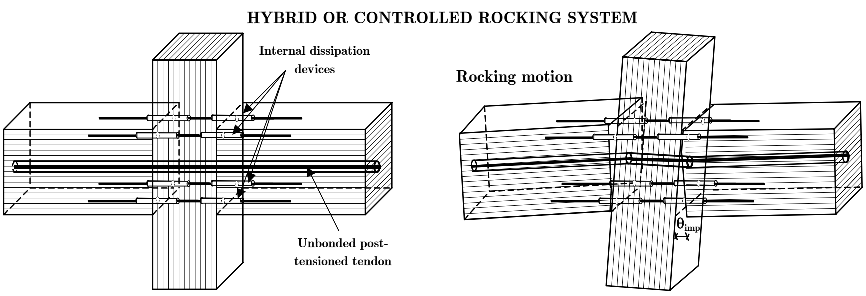


Figure 3. Basic concept of *hybrid* jointed ductile connections for LVL frame systems.

3.1 Controlled rocking mechanism at the connection interface

As shown in Fig. 4, in a post-tensioned jointed ductile connection a "controlled rocking" motion occurs with the opening and closing of an existing gap at the critical interface. When compared to pure rocking motion, the prestressing force (initial prestress plus additional contribution due to elongation of the tendons) provides a restoring force counteracting excessive opening (rotation demand), reversing the rocking motion, and closing the gap completely after an earthquake. The additional non-prestressed reinforcement can provide further limitations to the gap rotation demand, by increasing the strength of the connection as well as reducing the seismic demand (energy dissipation contribution).

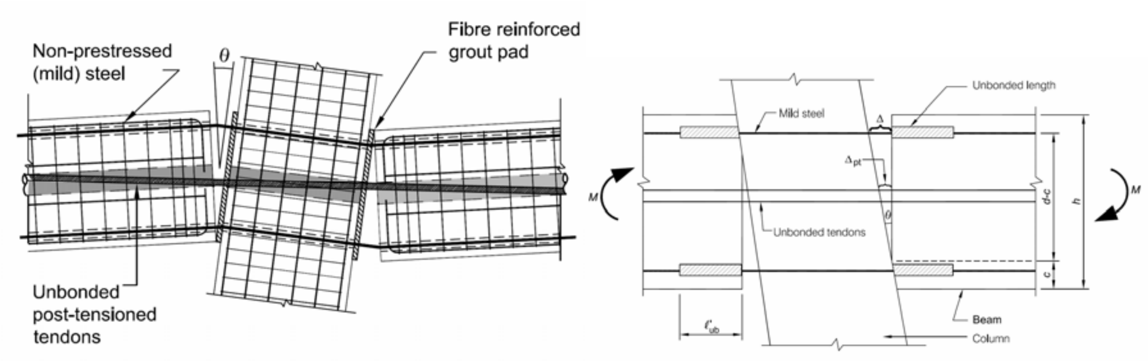


Figure 4. Controlled rocking mechanism at the critical connection in a hybrid beam-column connection (NZS3101:2006, Appendix B, after Pampanin et al., 2001).

Evaluation of flexural strength

Referring to the peculiar mechanism (gap opening and closing at the critical interface) of the hybrid beam-column connection shown in Figure 4, the strain levels in the unbonded post-tensioned tendons due to the gap rotation θ, $\varepsilon_{pt}(\theta)$, and in the non-prestressed steel reinforcement (with a short unbonded length at the critical section in the case of internal mild steel, to avoid premature fracture), $\varepsilon_s(\theta)$, can be evaluated by basic geometrical considerations as : $\varepsilon_{pt} = \frac{n\Delta_{pt}}{\ell_{ub}}$ and $\varepsilon_s = \frac{(\Delta_s - 2\Delta_{sp})}{\ell'_{ub}}$ respectively. where: n is the number of total joint openings along the beam (at beam-column interfaces); ℓ_{ub} and ℓ'_{ub} are the unbonded lengths in the tendons and in the non-prestressed steel reinforcement, respectively; Δ_{pt} and Δ_s, are the elongations at the level of the tendons and of the non-prestressed steel reinforcement respectively; Δ_{sp} is the elongation due to strain penetration of the non-prestressed steel reinforcement (assumed to occur at both ends of the unbonded region).

Once the position of the neutral axis and the value of the compression strain in the extreme LVL fiber is derived by translational equilibrium, the moment capacity can be simply derived by rotational equilibrium. However, due to the presence of unbonded post-tensioned tendons possibly in combination with partially epoxied longitudinal mild steel bars (or externally located dissipaters), or a combination of the above, the assumption of strain compatibility between the basic material (timber in this case) and the post-tensioned steel, typically required for a section analysis approach is violated at a section level. As a result, traditional cross section analysis methods typically adopted for the design or flexural strength evaluation of a section can not be directly applied to these systems. The special provisions for precast concrete jointed ductile connections in NZS3101:2006 adopt a simplified yet extensively validated procedure for the definition of the moment-rotation curve for connections with unbonded reinforcement where section strain compatibility assumption are violated. This is described by Pampanin et al. (2001) also adopted by the *fib* guidelines for the seismic design of precast concrete connections. Based on a member compatibility concept, the method, named “Monolithic-Beam-Analogy” (MBA) and further refined by Palermo (2004), relies on an analogy with equivalent monolithic solutions. Extensive experimental validations of the aforementioned general procedure for jointed ductile connections have been carried out for precast concrete beam-column joints, frames and shear walls (Pampanin et al., 2001; Palermo et al., 2005), as well as for concrete bridge piers (Hewes et al., 2002, Palermo et al., 2006) and for post-tensioned dissipating, PTED, steel frame solutions (Christopoulos et al. 2002a). Preliminary validation with the experimental results on LVL hybrid systems have provided satisfactory confirmation. Following the aforementioned moment-rotation procedure and on-going validation with the experimental tests, dimensionless design tables and charts related to different section shapes and reinforcement layouts are under preparation, as already done for precast concrete systems (Palermo, 2004).

4. General Design Philosophy and Criteria

4.1 Force-based or displacement-based design approach

Either a force-based or a displacement based design procedure can in principle be adopted for the design of jointed ductile systems, including those using timber members. The special provisions for jointed ductile systems and connections included in Appendix B of NZS3101:2006 are the first worldwide to suggest and allow the use of displacement design of jointed ductile connections.
Limits and drawbacks of traditional force-based design approaches have been well recognized and critically discussed in the literature (Priestley, 1998).A displacement-based design procedure would more naturally capture and control the peculiar rocking behaviour (the rotations at the critical interfaces) of these systems. According to a “flexible” design approach for hybrid systems proposed by Pampanin (2000), the self-centering and energy dissipation contributions of a hybrid system, recognized as key design parameters, can be adequately selected to control maximum displacement and limit residual displacement, while maintaining a given moment capacity. A framework for a Direct Displacement Based design procedure for generic hybrid systems, regardless of the material adopted, was proposed by Pampanin (2000). A more comprehensive displacement based design procedure for precast concrete jointed systems including design examples for frames and wall systems has been recently provided by Priestley (2002). Development of a displacement-based design procedure for timber LVL hybrid systems is continuing and will be presented in the future.

When using a force-based design approach, as typical of major seismic code provisions, appropriate values for the reduction factor R (or the behaviour factor q defined in Eurocode 8) should be defined. As mentioned, provided that an adequate amount of hysteretic damping is given to the flag-shape hysteretic rule, the performance of a hybrid system is expected to be at least as satisfactory as an equivalent monolithic ductile system. Numerical comparisons, again material-independent, between the seismic response of flag-shape and standard dissipating hysteresis loops (Pampanin, 2000, Christopoulos et al., 2002a, Palermo et al., 2006) have demonstrated that the maximum displacements, ductility or inter storey drift values of a hybrid system will be similar, provided that adequate dissipation capacity is given (in the order of 15% of equivalent viscous damping). Similar values for the reduction factors can thus be suggested for hybrid systems and their monolithic counterparts (Pampanin 2000), as recently adopted in Eurocode 8 for concentrated ductility connections. When designing timber structures, equivalent reduction or behaviour factors (R or q) typical of standard high-ductile connection (i.e. epoxied rods or multi-nailed connections) can be thus be adopted. Extensive numerical investigations are on-going to compare the seismic response of multi-storey timber buildings using traditional connections (i.e. plywood shear walls with nailed connections, or glulam frames with multi-nailed steel plates or epoxied rod connections) with the performance of hybrid (rocking/ dissipating) connections. It is anticipated that, given the relatively limited energy dissipation capacity of a multi-nailed connection due to the extensive "pinching" in the hysteresis loops when compared to the more stable flag-shape hysteresis loops provided by the alternative hybrid connections tested under simulated seismic loading, elastic spectra reduction (or behaviour) factors for these new solutions may be even higher than for conventional construction.

4.2 Controlling the flag-shape hysteresis behaviour: damping vs. re-centering

As consistently confirmed by the results of experimental results, (quasi-static or pseudo-dynamic tests) a wide range of hybrid solutions can be obtained, depending on the moment contribution ratio between self-centering and dissipating contribution, typically defined as $\lambda=M_{pt}/M_s$ where M_{pt} is the flexural strength contribution of the post-tensioning tendons and M_s is the flexural strength contribution of the energy dissipating devices.

Upper and lower bounds of an hybrid system would thus be given by a) a pure rocking system relying on unbonded post-tensioning and/or axial load to provide re-centering (behaviour described by a Non Linear Elastic rule) and b) a dissipative only system with non-prestressed reinforcement and typical elasto-plastic or similar hysteresis rule.

By combining, for a given target strength, the percentage of prestressed and non-prestressed reinforcement within the connection, or, better, the moment contributions between rocking (or re-centering) and energy the properties of the flag-shape hysteresis would vary accordingly (Figure 5) and could be controlled. In particular, it can be noted that the static (maximum feasible) residual deformation and the equivalent viscous damping evaluated from the hysteretic rule can be adopted as main design parameters. By increasing the moment contribution due to the post-tensioning, lower dissipation capacity will be obtained, thus leading to higher displacement demand. On the other hand, a low contribution from the post-tensioning, could impair the re-centering capacity, thus leading to not-negligible residual deformations and a higher cost of repair. Ultimately, a balanced combination of prestressed and non-prestressed steel given by a adequately selected value of $\lambda = M_{pt} / M_s$ can control the maximum lateral displacement, expected under a design level of earthquake intensity, under target limits in accordance with performance based design considerations, while guaranteeing minimum values of residual deformations.

Simplified design charts such as those shown in Figure 5 can be used to define an adequate ratio $\lambda = M_{pt} / M_s$ in the preliminary design phase in order to satisfy the desired requirements.

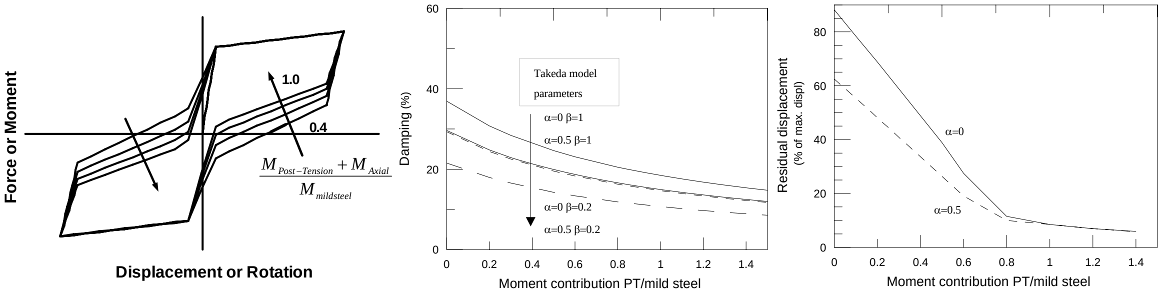


Figure 5 – Influence of the moment contribution ratio λ between post-tensioning steel (PT) and non-prestressed steel on the flag-shape hysteresis of a hybrid system. and on its key parameters (equivalent viscous damping and static residual (Pampanin, 2000; fib, 2003, NZS3101:2006)

4.3 Targeting fully re-centering behaviour

As anticipated, a full re-centering capacity can be achieved at a connection level when the tendons are able to overcome the resistance of the dissipaters and re-close the gap. When using ordinary yielding devices to dissipate the energy, the tendon's restoring moment must be sufficient to yield back in compression the non-prestressed steel which has previously yielded in tension.

In general, regardless of the material and the dissipation systems adopted, a fully re-centering condition can be obtained by selecting an appropriate moment contribution ratio $\lambda \geq 1$. Material overstrength due to steel hardening and Bauschinger effects should be accounted for. In this regard, the NZS3101:2006 guidelines suggest a value of $\lambda \geq \alpha_0$, where α_0 is the expected material overstrength for the non-prestressed steel reinforcement or the energy dissipation devices. In absence of clear information a value of $\alpha_0 \geq 1.15$ (thus $\lambda \geq 1.15$) should be adopted. As a result of a full-re-centering requirement or targeted behaviour, the value of the initial prestress in the tendon are bounded by lower and upper limits. A minimum amount of initial prestress should be used (lower bound) to guarantee the target strength as well as the desired re-centering contribution at a target drift level. Additionally, if coulomb friction due to the post-tensioning is relied upon for partial transfer of shear force (typically seismic shear component) at the critical interface (as in a beam-column connection) a minimum prestress level should be guaranteed at all times. On the other hand, a maximum level of initial prestress should be adopted (upper bound) in order to ensure that the tendons remain in the elastic range at the target inter storey drift levels.

5. Experimental Validation of LVL Hybrid Connections

An extensive research program has been planned and partly carried out at the University of Canterbury to investigate the seismic performance of innovative LVL jointed ductile connections for application in multi-storey timber buildings consisting of seismic resisting frames and/or walls and floors. The program, divided in three phases, involves both comprehensive numerical and experimental investigations at subassembly level (beam-column, column-to-foundation) and global level (whole frames or walls in the complete building). A brief overview is given here, confirming the high performance of the developed solutions and reliability of the design approach. More details can be found in recent publications (Palermo et al. 2005, 2006a, 2006b). The numerical and experimental investigations have provided excellent confirmation of the efficiency of hybrid solutions in multi-storey LVL buildings in seismic regions.

Either quasi-static or pseudo-dynamic tests have been carried out on exterior beam-column subassemblies, wall-to foundation as well as column-to foundation connections. Typical test-setups are shown in Fig. 6. Yielding-type dissipaters have been provided, consisting of deformed mild steel bars machined down to guarantee fuse action, either epoxied inside the main structural elements or located externally. Figure 7 shows details of the construction process and final appearance of typical internal and external dissipaters for the beam-column subassemblies.

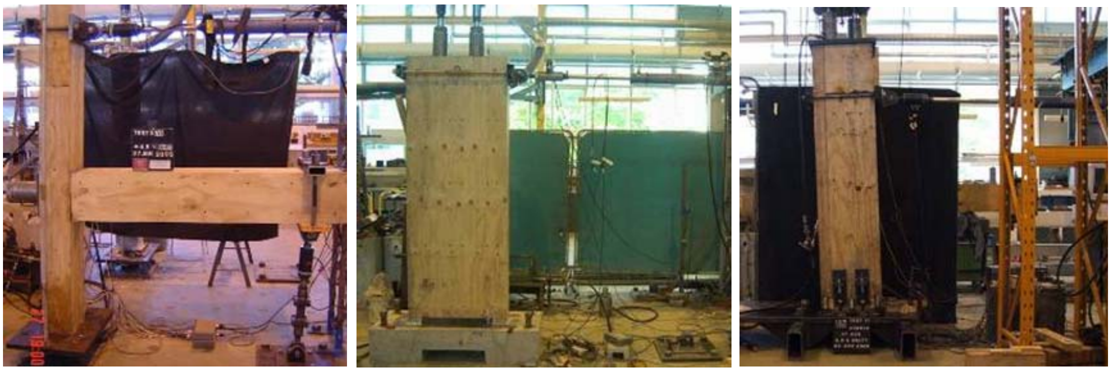


Figure 6. Test set-up of Exterior beam-column, wall-to-foundation, column-to-foundation specimens.

INTERNAL DISSIPATERS:
epoxied mild steel bars with unbonded length

EXTERNAL DISSIPATERS:
mild steel rods with epoxied encased steel tubes

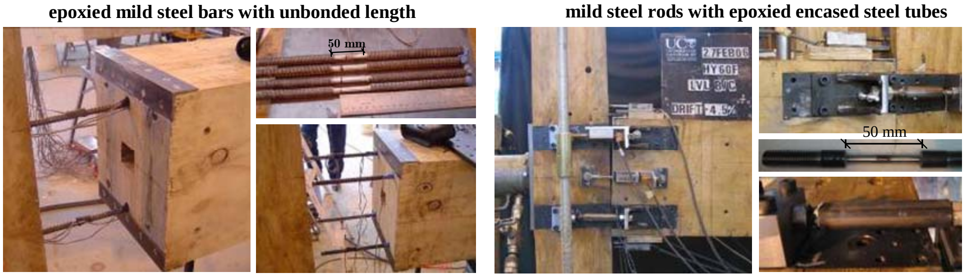
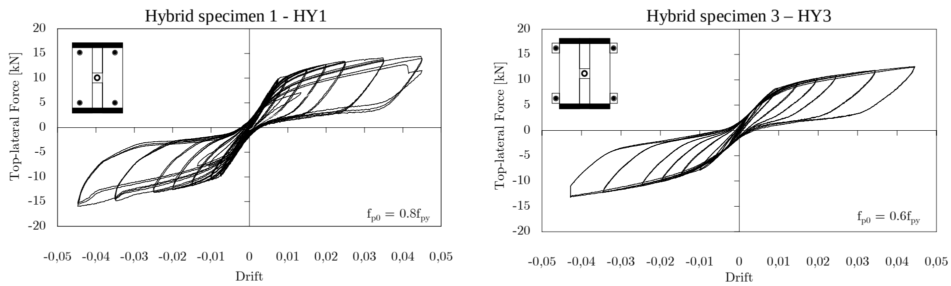


Figure7. Construction details of beam-column subassemblies with internal and external dissipaters.

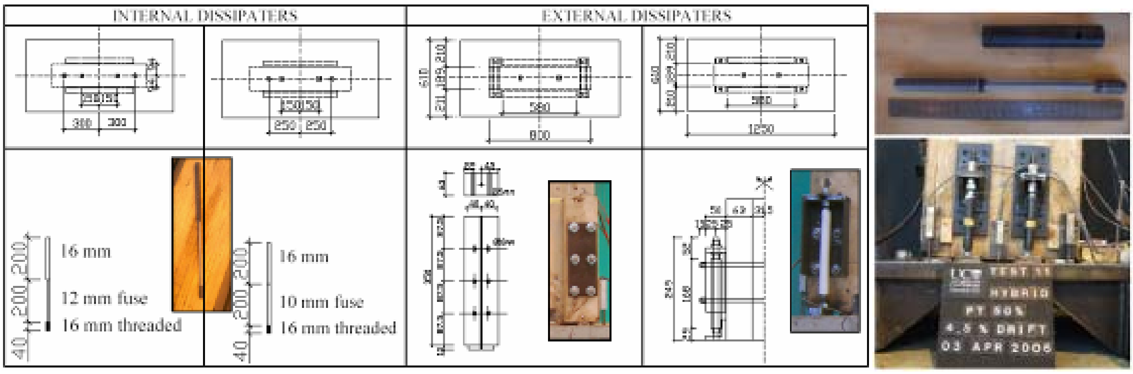
Following the design principles outlined above, the size, location and other details of the dissipaters and the location and initial prestress of the post-tensioned tendons were carefully designed to guarantee different target levels of re-centering vs. dissipating contribution (moment ratio, λ) while maintaining a flag-shape response.



a) b)

Figure 8: Hysteresis force vs. drift response of hybrid solution beam-column joint: a) hybrid solution with internal dissipaters; b) hybrid solution with external dissipaters

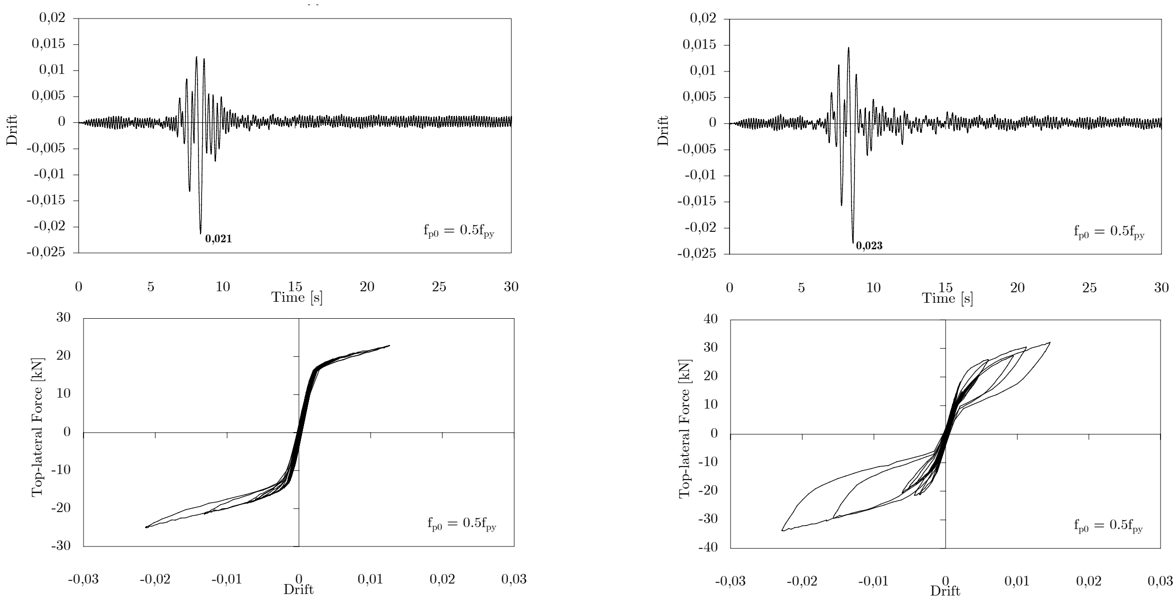
The experimental results have confirmed the unique design flexibility of hybrid connections, where similar force-drift (or moment-rotation) capacity envelopes associated with different values of λ have been consistently found, as shown in Figure 8a (internal dissipaters) and Figure 8b (external dissipaters), where the force-displacement curves of four tests on exterior beam-column subassemblies are represented. It can be seen that the overall force-drift envelope curve of the specimen HY1 is very similar to HY3 despite the adoption of a different combination of dissipaters (internal vs. external, with different unbonded lengths) and initial post-tensioning forces ($0.8f_{py}$ vs. $0.6f_{py}$, respectively). Several unbonded post-tensioned-only configurations have also been tested with different levels of the initial post-tensioning force. Similar design procedures and connections details have been implemented for wall-foundation (Fig. 9a) and column-foundation (Fig. 9b) specimens.



a) b)

Figure 9: a) Details of internal and external dissipaters used for the wall specimens;
b) dissipaters detail for of the column-to-foundation specimens.

The results of a series of pseudo-dynamic tests on wall-foundation and column-foundation connections under different level of seismic intensity, confirmed the excellent performance of the post-tensioned/dissipating solutions. Depending on the seismic intensity of the region or on the targeted performance level, alternative arrangements can be obtained by using different combination of tendons and dissipaters. As confirmed by previous studies and applications on precast concrete connections (Pampanin et al., 2005), it is worth noting that in low-to-moderate seismic regions the use of post-tensioning alone, without additional dissipation devices, can be sufficient to control the deflection within targeted (desired or acceptable) levels.



a) b)

Figure 10 Pseudo-dynamic experimental test response of cantilever column-to-foundation systems a) unbonded post-tensioned only (under 100% input motion) b) hybrid system (under 150% input motion)

Multi-storey timber post-tensioned buildings could thus represent a very efficient solution for most of "gravity load dominated" structures. The additional use of dissipaters, would not only enhance the overall strength but also the energy dissipation contribution, thus meeting similar code-based displacement or drift limits in higher seismic region. This concept is clearly illustrated in Figure 10: two alternative solutions, one post-tensioned-only and one hybrid, have been designed according to a displacement based design procedure to achieve similar target drift (around 2-2.5 %) when subjected to two different levels of seismic input intensity (100% and 150% of an earthquake record from the Loma Prieta event, 1989) corresponding to a different earthquake return period (e.g. 500 years and 2500 years respectively). As expected, a non-linear hysteresis response is emphasized by the unbonded post-tensioned-only solutions with a small amount of dissipation due to minor plastic deformation of the LVL material in the compression zone, while a typical flag-shape hysteresis with higher strength is obtained by the solutions with additional external dissipaters, which yielded at around 0.7% of drift. Confirming the reliability of the design procedure, both systems showed similar maximum drift response (2.1% and 2.3% drift respectively) while maintaining negligible residual deformations (full re-centering condition respected). Furthermore, in both cases and in spite of the drift level achieved, no appreciable damage was observed.

6. Conclusions

Innovative damage-resistant solutions have been developed for the seismic design of multi-storey LVL timber buildings, following current international trends towards performance based seismic design and technological solutions for high seismic performance, based on limited levels of damage. The results of an ongoing extensive experimental campaign have confirmed the enhanced performance of jointed ductile connections (also referred to as hybrid systems) with a combination of post-tensioned tendons and energy dissipaters. When compared to traditional solutions widely used in timber construction (e.g. nailed, bolted or steel dowel connections) limited levels of damage can be achieved thanks to controlled rocking mechanisms at the critical connection interfaces. Re-centering properties, leading to negligible residual deformations and limited cost of structural repairing, are provided by unbonded post-tensioned tendons. Simple and reliable design and modelling procedures, developed for precast concrete structures and implemented in major seismic codes, can be adopted with minor modifications for the design of innovative high performance LVL structures and can be proposed for adoption in the next generation of timber design codes and guidelines. It is clearly anticipated that the flexibility of design and the speed of construction of prefabricated LVL buildings, combined with the intrinsic enhanced seismic performance of hybrid systems, creates unique potential for future development and increased use of this type of construction in low-rise multi-storey buildings on a world scale.

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