Uni and Bi-directional Quasi Static Tests on Alternative Hybrid Precast Beam Column Joint Subassemblies

A. Amaris, & S. Pampanin

Department of Civil Engineering, University of Canterbury, Christchurch.

A. Palermo

Department of Structural Engineering, Technical University of Milan, Italy

2006 NZSEE Conference

ABSTRACT: Recent developments on high performance seismic resisting precast concrete frame systems, based on the use of unbonded post-tensioned tendons with self-centring capabilities in combination with additional sources of energy dissipation, are herein presented. Alternative arrangements for jointed ductile connections to accommodate different structural or architectural needs have been implemented and validated through quasi-static cyclic tests on a series of 2/3 scaled beam-column subassemblies under uni- or bi-directional loading regime. The satisfactory results confirmed the unique flexibility and potentiality of the proposed solutions for the development of the next generation of seismic resisting buildings.

1 INTRODUCTION

Several alternative solutions to provide moment-resisting connections between precast elements for seismic resistance have been studied in the past and developed in literature (Watanabe et al 2000, Park 2002, fib Bulletin No. 27 2003) mostly relying on cast-in-place techniques to provide equivalent "monolithic" connections (i.e. equivalent strength and toughness to their cast-in-place counterparts). As implicit in a traditionally accepted seismic design approach, based on the development of a desired inelastic mechanism through the formation of plastic hinge regions in the discrete and controlled locations within the structure (i.e. weak beam, strong column mechanism), different levels of structural damage and, consequently, repair cost, will be expected and, depending on the seismic intensity, typically accepted as unavoidable results of the inelastic behaviour itself.

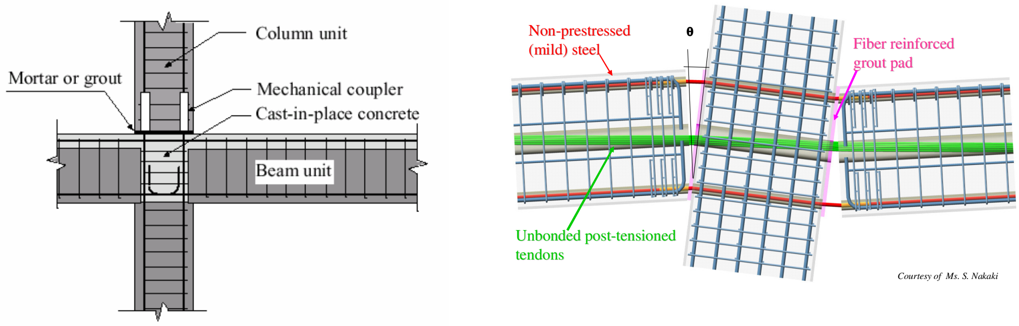

Figure 1. Emulation of cast-in-place concrete vs. jointed ductile hybrid solutions.

In the last decade, a revolutionary alternative approach in seismic design, has been introduced in the solutions developed under the U.S. PRESSS program coordinated by the University of California, San Diego (Priestley 1991, Priestley 1996, Priestley et al. 1999) for precast concrete buildings in seismic regions with the introduction of "dry" jointed ductile systems (Figure 1, right side), as an alternative to the traditional emulation of cast-in-place solutions and based on the use of unbonded post-tensioning techniques. As a result, high seismic performance structural systems can be obtained, with the unique potentiality to undergo inelastic displacement similar to their traditional monolithic counterparts, while limiting the damage to the structural system and assuring full re-centring capabilities (negligible residual or permanent deformations).

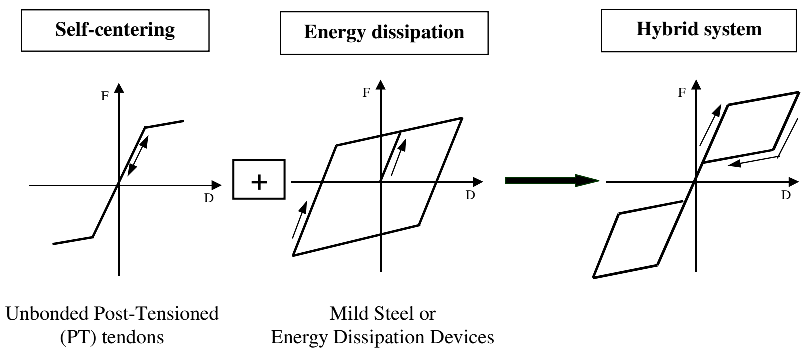

Figure 2. Idealized flag-shape hysteretic rule for a hybrid system (fib Bulletin No. 27 2003).

A sort of "controlled rocking" motion of the beam (Figure 1, left side) or wall panel occurs, while the relative ratio of moment contribution between post-tensioning and mild steel (typically referred to as λ parameter) governs the so-called "flag-shaped" hysteresis behaviour (Figure 2).

A comprehensive overview of developments on high-performance seismic resisting precast/prestressed systems based on jointed ductile connections has been recently given by Pampanin (Pampanin, 2005). In addition to the relative contribution between recentring and dissipation capacity, main key features differentiating alternative solutions for hybrid systems for seismic resisting frames can be given by: a) the longitudinal profile of post-tensioned tendons: straight, draped tendons/cable profile solutions or combinations of the above depending on the contribution of the gravity and lateral loads effects; b) the type, sources and location of energy dissipation: internal or external supplemental damping device relying on metallic or advanced materials (e.g. shape memory alloys, visco-elastic systems) and implemented following a passive or semi-active control approach; c) the shear transfer mechanism at the critical interface: relying either on friction due to the post-tensioned tendons contribution, or on ad-hoc shear keys or steel corbel.

2 EXPERIMENTAL INVESTIGATION ON ALTERNATIVE HYBRID SYSTEM SOLUTIONS

In the following paragraphs, an up-to-date summary of recent results obtained as part of an extensive experimental research campaign on going at the University of Canterbury on the refinement and further development of alternative arrangements for hybrid precast/prestressed building systems will be provided. Particular attention will be given to the quasi-static cyclic test, under uni- and bi-directional testing regime, on a series of exterior 2-D or 3-D beam-column joint subassemblies, 2/3 scaled, to evaluate the performance of recently implemented concepts and details as well as to validate the efficiency of the analytical models used for design and analysis purposes.

According to the previously defined key features of alternative hybrid systems, alternative tested configurations comprised solutions with either straight or parabolic tendons, relying on either unbonded post-tensioned tendons only or on the addition of internal or external energy dissipators. Thanks to the peculiar "undamageable" properties of a hybrid system, where only the energy dissipators act as sacrificial fuses and might be required to be substituted after a test (or after an earthquake event), only a few (three at this stage) very flexible modular specimens had to be repaired.

The typical set-up and imposed displacement regime of the beam-column joint subassemblies are shown in Figure 3. Beam and column elements are extended between points of contra flexure, assumed to be at mid-span of the beams and at mid-height of the columns, where pins are introduced. Simple supports at the beam ends were provided by connecting pin-end steel members to the floor.

Quasi-static cyclic tests were carried out under increasing levels of lateral top displacement. The testing protocol complied with the "acceptance criteria" proposed in (ACI T1.1-01 & ACI T1.1R-01 2001) and consisted of a series of three cycles of drift, followed by a smaller single cycle.

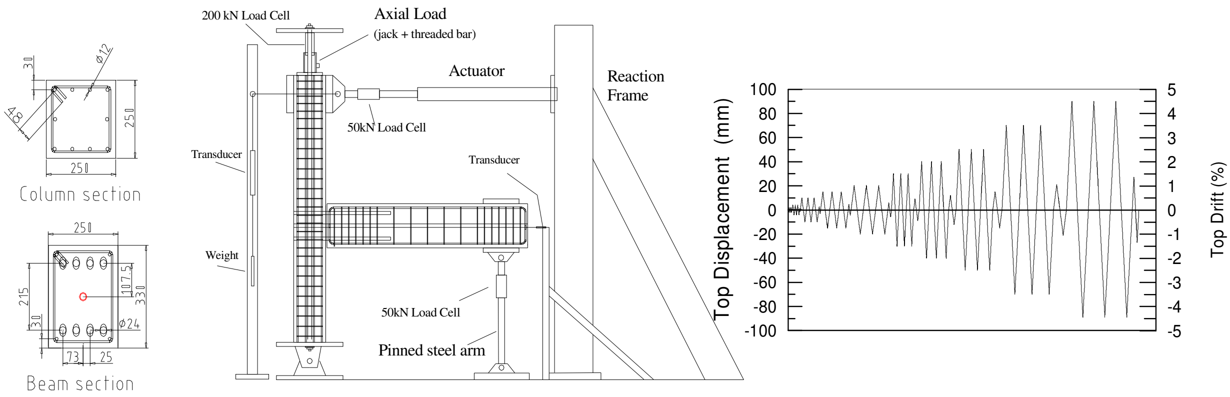

Figure 3. General uni-directional test set-up and loading protocol.

3 TRADITIONAL PRESSS-TYPE HYBRID SYSTEM

A first series of tests was carried out to reproduce the basic configuration of a hybrid PRESSS system (modular specimen type 1) as originally proposed by Stanton et al. (Stanton et al. 1997). The specimen comprised a) straight profile longitudinal tendons; b) internal mild steel bars as dissipation devices c) friction at the critical beam-column section as the shear transfer mechanism (Figs. 3 and 4). At the rocking interface, steel plates were embedded on one side of the column and one edge of the beam in order to allow a detailed investigation of the effects of alternative contact surfaces: concrete-concrete, steel-concrete, steel-steel with and without a (fibre reinforced) grout pad to accommodate the construction tolerances.

3.1 Response of Unbonded Post-Tensioned-only Solution

Tests were first carried out on unbonded post-tensioned solutions only, varying the level of initial post-tensioning as well as the contact surface at the beam-column interface. In general the behaviour of the different arrangements was satisfactory, with a stable non linear elastic hysteresis without remarkable losses of stiffness at any reloading stage, except for the solution using a 50mm interface grout pad (reinforced with a fiber mesh), which tended to become the most vulnerable element of the connection. Figure 4 shows the opening of the gap at 4.5% drift and the hysteretic behaviour for a post-tensioned solution (with steel-concrete contact surfaces). A seven wire strand (A_{pt} = 99mm^2) was used with an initial post-tensioning at 60% of the ultimate stress f_{ptu} (1860MPa), thus equal to an initial post-tensioning force of approximately 110kN. Typical of a jointed ductile hybrid solution, no damage was reported in the structural members, while a very stable full re-centring non-linear elastic hysteresis loop was developed, the geometric non-linearity being due to the sudden relocation of the neutral axis along the section depth.

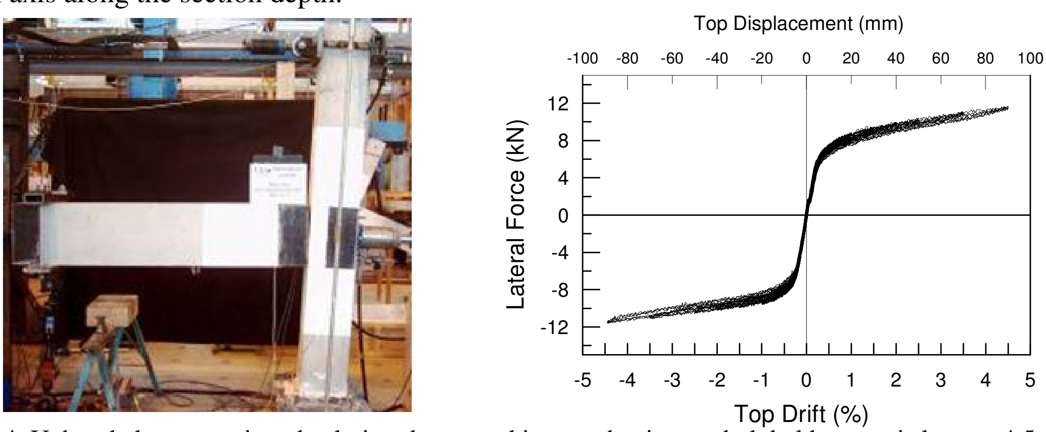

Figure 4. Unbonded post-tensioned solution: beam rocking mechanism and global hysteresis loop at 4.5 % drift.

3.2 Response of Traditional PRESSS Hybrid Solution

Following the original version of the PRESSS hybrid system, additional energy dissipation capability was added to the unbonded post-tensioned solution in the form of four longitudinal mild steel reinforcing bars (10mm diameter), inserted in embedded metallic corrugated ducts and successively grouted (Figure 5, left side). In order to prevent premature fracturing of the steel, a small unbonded length of 60mm was adopted by wrapping plastic tape around the bars in the proximity of the critical section. The same initial post-tensioning as in the post-tensioned only solution was applied to the seven wire tendon (i.e. 110kN equal to $60\%f_{ptu}$) to evaluate and confirm the effects of the additional internal dissipators. The experimental results, presented in Figure 5 (right side) and referring to a steel – concrete contact, highlighted a very stable flag shape behaviour with high dissipation as well as re-centring properties up to 4.5% drift. The onset of stiffness degradation due to the bond deterioration between the longitudinal mild steel bars and the injected grout became more evident at the first cycle at 4.5% of drift. It is worth noting that, in order to have full recentring capabilities, minor modification to the design (i.e. a lower level of dissipation and/or higher post-tensioning), could be implemented to guarantee a moment contribution λ bigger than 1.

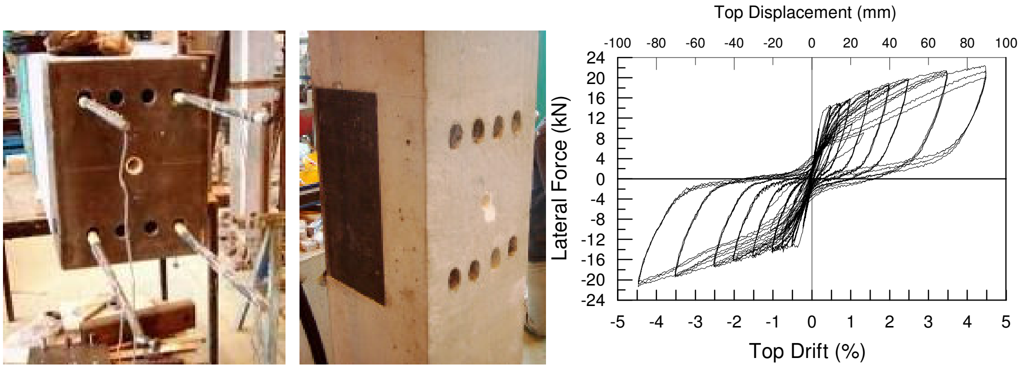

Figure 5. Hybrid PRESSS system with internal dissipators: construction details of beam and column, unbonded length in the mild steel bars and hysteresis loop.

4 USE OF DRAPED TENDON PROFILE AND SHEAR KEY

Based on similar concepts, a peculiar connection solution and construction system, named the "Brooklyn" system, has been studied and developed in Italy for gravity-load-dominated frame buildings with the intent of combining the structural concept and efficiency of cable-stayed or suspended bridges within a typical multi-storey building system (Pagani 2001, Pampanin et al. 2004).

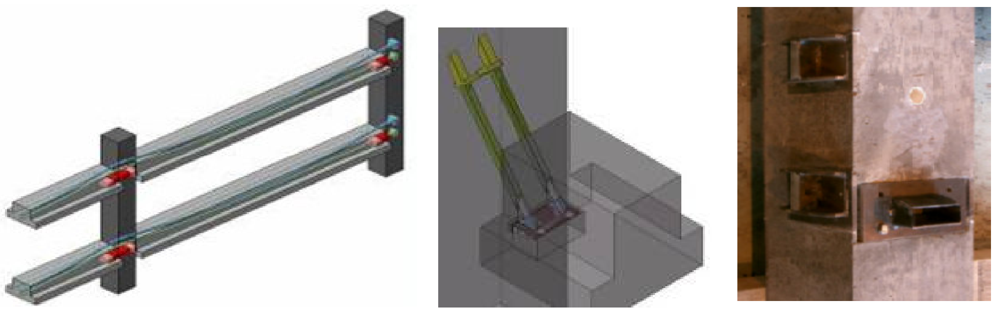

Figure 6. a)Brooklyn system: suspended solution. b) cable-stayed version of the hidden steel bracket (Pampanin 2005, Pampanin et al. 2004) .c) Details of arrangement for external dissipators and simplified shear key/corbel.

Key peculiarities of the system are:

a) the use of a draped tendon profile ("suspended" solution, Figure 6 left side) anchored at the exterior columns of the frame in order to supply an adequate moment resistance at the critical sections under combined gravity and low-to-moderate lateral loads;

b) the use of alternative solutions for steel shear bracket/corbel (Figure 6 right side), able to fully counteract the shear force transmitted at the beam-column interface. In this way the prestressing tendons have only to balance flexural stresses and a large floor slab span (e.g. 10 x 12 m grid) can be achieved. Undesirable consequences related to the yielding or failure of the tendons, or in general, due to the loss of the shear friction transfer mechanism, are thus overcome, in line with recent requirements in code provisions (e.g. NZS3101, (SNZ, 2005)). Also, by "hiding" the corbel in the depth of the beam, architectural and aesthetic requirements (in addition to fire resistance) can be met.

An overview of the conceptual definition, development and experimental validation (under either gravity or seismic loads only) of the solution, including a description of practical applications on a series of buildings in regions of low-moderate seismicity can be found in Pampanin et al. (2004, 2006). Figure 7 shows experimental results in terms of the global force-displacement hysteretic behaviour.

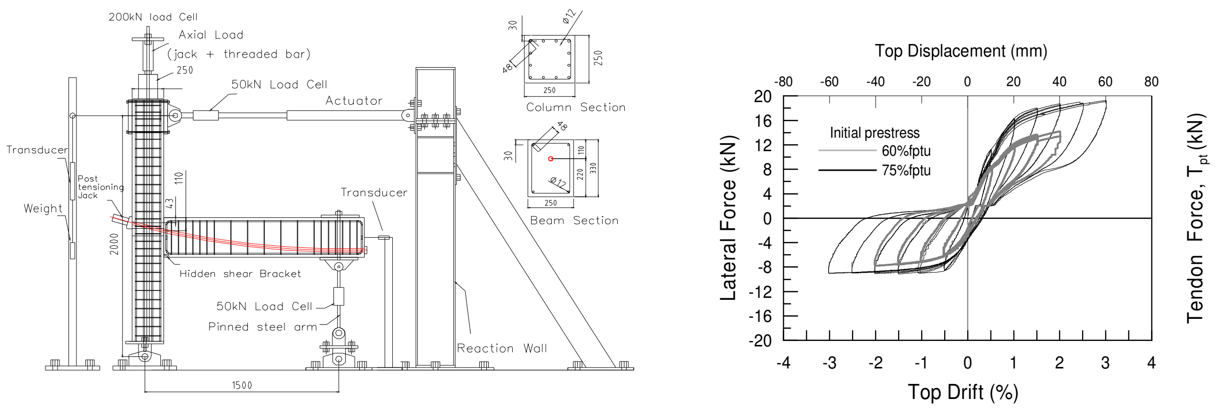

Figure 7. PRESSS-Brooklyn hybrid beam-column subassembly with external dissipators: test set-up and flag-shape forced-displacement hysteresis when varying the level of prestress

5 EXPERIMENTAL RESPONSE UNDER BI-DIRECTIONAL CYCLING LOADING

Previous tests described in literature on jointed ductile precast hybrid systems have typically referred to 2-D beam-column subassemblies belonging to plane frame systems. As part of the experimental research investigation herein reported, a 3-D exterior (corner) beam-column joint subassembly, part of a space frame, was prepared with a modular configuration (type 2), such that several alternative arrangements of hybrid systems could be tested, after replacing the dissipating devices.

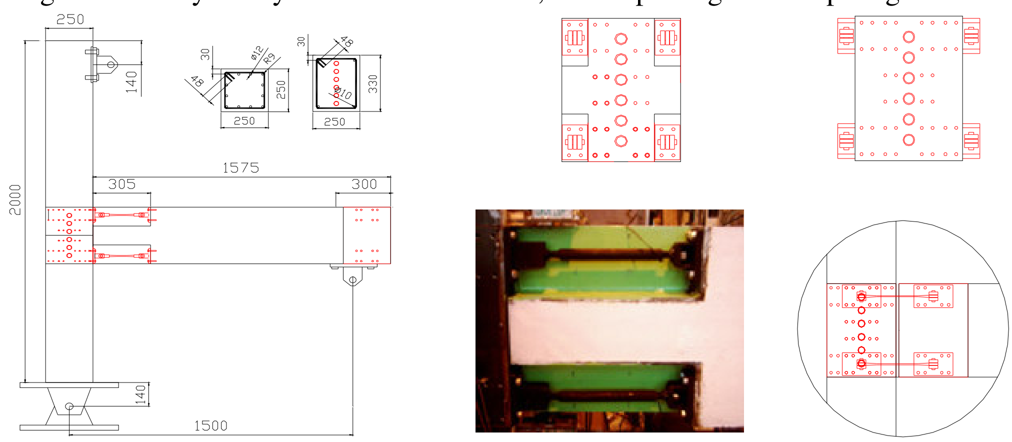

Figure 8. 3-D modular configuration of the Hybrid beam-column joint: location of hinges and dissipators.

A flexible face plate, acting as a sort of "mask", was located at both the beam and column faces with different possible locations of the mechanical hinges acting as shear key solutions. As shown in Figure 8, five different positions of hinges and six different locations of the unbonded tendon profiles could be tested. The location of the dissipators could also be either within the beam rectangular lateral profile (thus "hidden" for architectural requirements) or external to it.

The 3D specimen was subject to a combined bidirectional "four cloves" loading protocol shown in Figure 9. Three cycles per combined drift level, plus one smaller amplitude cycle, were undertaken in each quadrant, with a similar conceptual protocol to that adopted for the uni-directional testing (ACI T1.1-01 & ACI T1.1R-01 2001). As a result, it is worth noting that the specimen is actually subjected to a more demanding protocol, with a cumulative number of six cycles in each direction per drift level, instead of the three cycles in the uni-directional testing protocol.

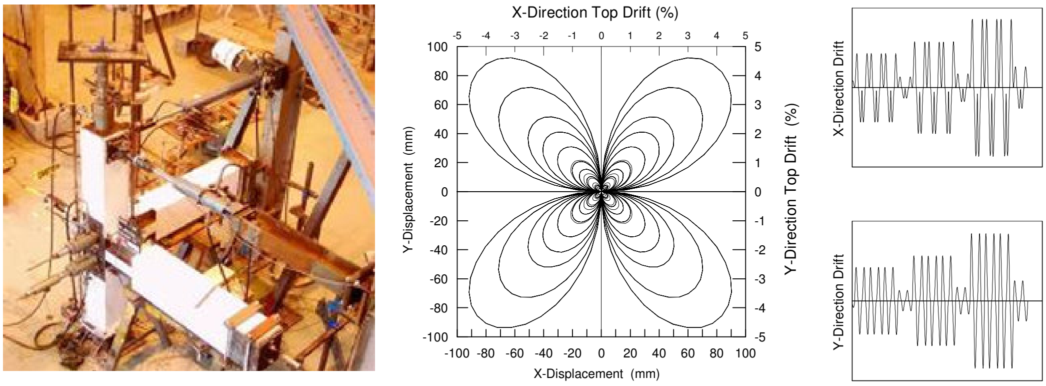

Figure 9. Test set-up and "four clove" bi-directional displacement regimes.

5.1 Unbonded Post-Tensioned-only Solution

In the unbonded post-tensioned only solution, the initial prestress forces were designed in order to obtain a similar target moment capacity in both directions at 4.5% drift. The different location of the tendons in the two beams (i.e. alternated in order to avoid clashing in the column region, see Figure 10), had to be accounted for. As a result, the initial post-tensioning forces were 15%f_{ptu} (27.5kN) and 27%f_{ptu} (49.5kN) in the X and Y directions respectively. In this 3-D configuration, the double hinge shear key, consisted of small metallic spheres (Figure 10 left side).

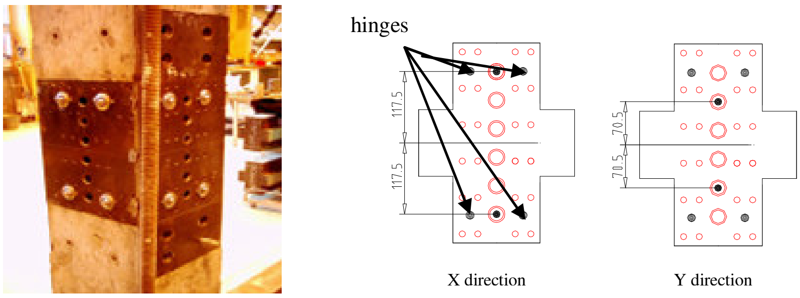

Figure 10. Location of the "double hinge" shear keys and location of the tendons in the two directions.

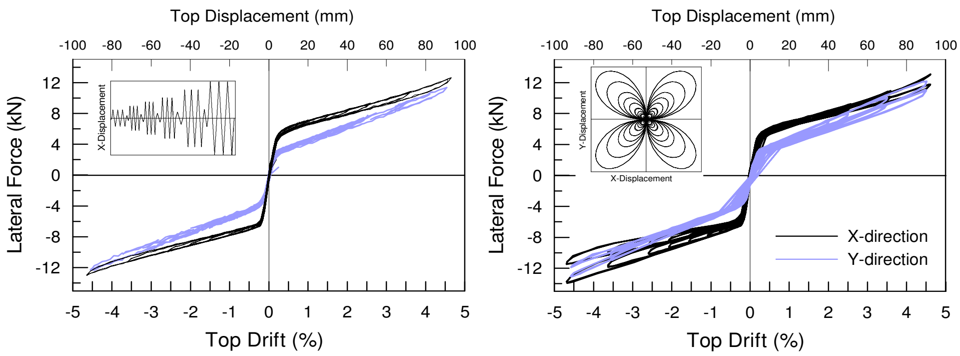

Figure 11. Force-displacement response of 3-D post-tensioned only solution under independent uni-directional (left) or combined "four cloves" (right) testing regime.

As shown in Figure 11, the response of the system was extremely satisfactory in both directions. The effects of bi-axial cyclic loading were almost negligible when comparing the response to that of the same specimen under independent uni-directional loading. An increasing level of damage or reduction of strength/stiffness was not observed, as would be expected in a monolithic configuration.

Nevertheless, the onset of beam torsion due to minor constraints in the test set-up (movement of the beam pinned arm in the out-of plane direction) occurred at a high drift level (4.5%) leading to minor losses of prestress in the tendons.

5.2 Hybrid Solution with External Dissipators

The hybrid solutions were obtained by adding external dissipators, with the clear aim of demonstrating the flexibility of the design and the possibility of having a reliable control of the flag-shape behaviour. The same moment capacity at target drift (4.5%) and similar energy dissipation were thus aimed for. Given the same tendon layout in the two directions as in the post-tensioned only solution (Figure 11), initial prestresses in the X and Y-directions were respectively, 25%f_{ptu} (i.e. 46kN) and 27%f_{ptu} (49.7kN).

Four external dissipators consisting of either 7 or 8 mm diameter fuses (with 150 mm unbonded length) were installed, in the X and Y directions respectively, and inserted ("hidden") in existing slots on both sides of the beam (Figure 8). The experimental response under uni-directional testing, i.e. X and Y-direction independently, showed (Figure 12 top) an extremely efficient and stable hysteresis loop. Valuable confirmations of the reliability of a flexible design approach were obtained, where dissipators, post-tensioner location and levels can be varied while maintaining the desired level of moment capacity and overall dissipation/recentring properties. The presence of the double-hinge shear key solutions (small metallic balls, Figure 10) guaranteed two fixed pivot points, with no stiffness or strength losses up to a high level of drift (4.5%) because of only minor damage at the contact level.

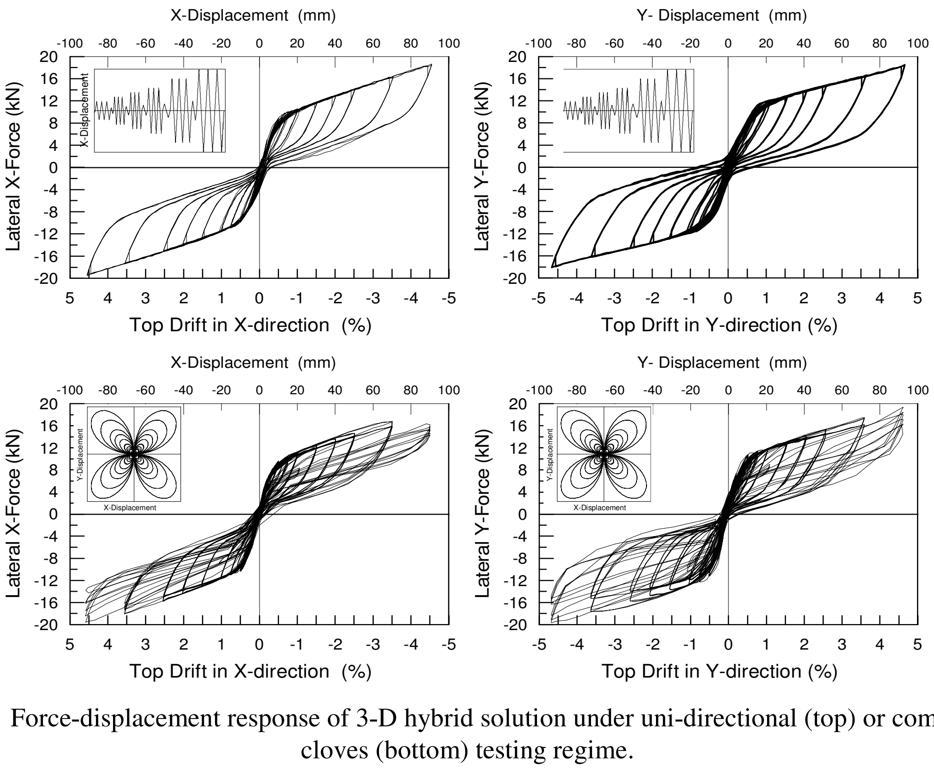

Figure 12. Force-displacement response of 3-D hybrid solution under uni-directional (top) or combined four cloves (bottom) testing regime.

The response of the hybrid system under the bi-directional (four clove) testing regime was very satisfactory up to 3.5% of drift. Up to this stage, the effects of bi-axial loading seemed to be negligible, when compared with the uni-directional response. At higher level of drifts, however, the torsion effects on the beam, observed during the tests on the post-tensioned solution and mainly due to the test set-up constraints, led to losses of prestress in the tendon as well as to general stiffness degradation. The subsequent increased level of strain demand in the dissipators, combined with the aforementioned highly demanding testing protocol, led to the premature fracture of dissipators when moving to 4.5% drift in the X-direction.

6 CONCLUSIONS

The implementation and experimental validation of several arrangements for precast jointed ductile connections, relying on unbonded post-tensioning techniques have been presented. Alternative configurations could be obtained by varying the longitudinal profile of the tendons, the type and location of the energy dissipation devices as well the shear transfer mechanism at the rocking critical section. Quasi static tests on a series of exterior beam-column joint subassemblies have been carried out under either uni- or bi-directional loading regimes and critically discussed. In general, a very satisfactory performance of the several alternative configurations was observed, which further underlines the high flexibility of the hybrid systems. Not only the global flag-shape behaviour can be controlled by properly designing the contribution between dissipation and recentring properties, but also, at this stage, the most appropriate technological solution can be chosen within a wide range of available connections/systems on a case-by-case basis.

ACKNOWLEDGEMENTS

The financial support provided by the NZ Earthquake Commission (EQC) and by the NZ Foundation of Research, Science and Technology ("Future Building System" research project) is greatly appreciated.

REFERENCES:

ACI T1.1-01 & ACI T1.1R-01 2001. (2001). "Acceptance Criteria for Moment Frames Based on Structural Testing (T1.1-01) and Commentary (T1.1R-01)." ACI Innovation Task Group 1 and Collaborators.

fib (2003), "International Federation for Structural Concrete. Seismic Design of Precast Concrete Building Structures." Bulletin No. 27, Lausanne, 254 pp.

SNZ (2005) DRAFT NZS3101:2005. (2005). "Appendix B: Special Provisions for the Seismic Design of Ductile Jointed Precast Concrete Structural Systems." Standards New Zealand, Wellington, New Zealand.

Pagani C. (2001). "Four is better than two – The principle of cable-stayed bridges applied to building beams." Elite International Journal on the Art of Prefabrication, 4, 50-69.

Pampanin S, Pagani C, Zambelli S. (2004). "Cable-stayed and Suspended Post-tensioned Solutions for Precast Concrete Frames:the Brooklyn System." Proceedings of New Zealand Concrete Industry Conference, Queenstown, New Zealand.

Pampanin S. (2005). "Emerging Solutions for High Seismic Performance of Precast/Prestressed Concrete Buildings." Journal of Advanced Concrete Technology (ACT), invited paper for Special Issue on "High performance systems", 3(2), 202-223.

Pampanin S, Palermo A, Amaris A. (2006). "Implementation and Testing of Advanced Solutions for Jointed Ductile Seismic Resisting Frames." Proceedings of the 2nd International fib Congress. Naples, Italy.

Park R. (2002). "Seismic Design and Construction of Precast Concrete Buildings in New Zealand." PCI Journal, 47(5), 60-75.

Priestley MJN. (1991). "Overview of the PRESSS Research Programme." PCI Journal. 36(4), 50-57.

Priestley MJN. (1996). "The PRESSS Program Current Status and Proposed Plans for Phase III." PCI Journal, 41(2), 22-40.

Priestley MJN, Sritharan S, Conley JR, Pampanin S. (1999). "Preliminary Results and Conclusions from the PRESSS Five-Storey Precast Concrete Test-Building." PCI Journal, 44(6), 42-67.

Stanton JF, Stone WC and Cheok GS. (1997). "A Hybrid Reinforced Precast Frame for Seismic Region." PCI Journal, 42 (2), 20-32.

Watanabe F. (2000). "Seismic Design for Prefabricated and Prestressed Concrete Moment Resisting Frames." Proceedings of the 46th PCI Annual Convention, Orlando, Florida.