7 DAMAGE RESISTANT DESIGN OF CONCRETE STRUCTURES

7.1 Jointed Ductile "Articulated" Systems – PRESSS-technology

In PRESSS (PREcast Seismic Structural System) frame or wall systems (Figure6.1), precast concrete elements are jointed together with unbonded post-tensioning tendons or steel bars creating a moment-resisting structure, with all the advantages associated with such a robust structural scheme. Full scale testing of frames and walls is shown in Figure 7.1.

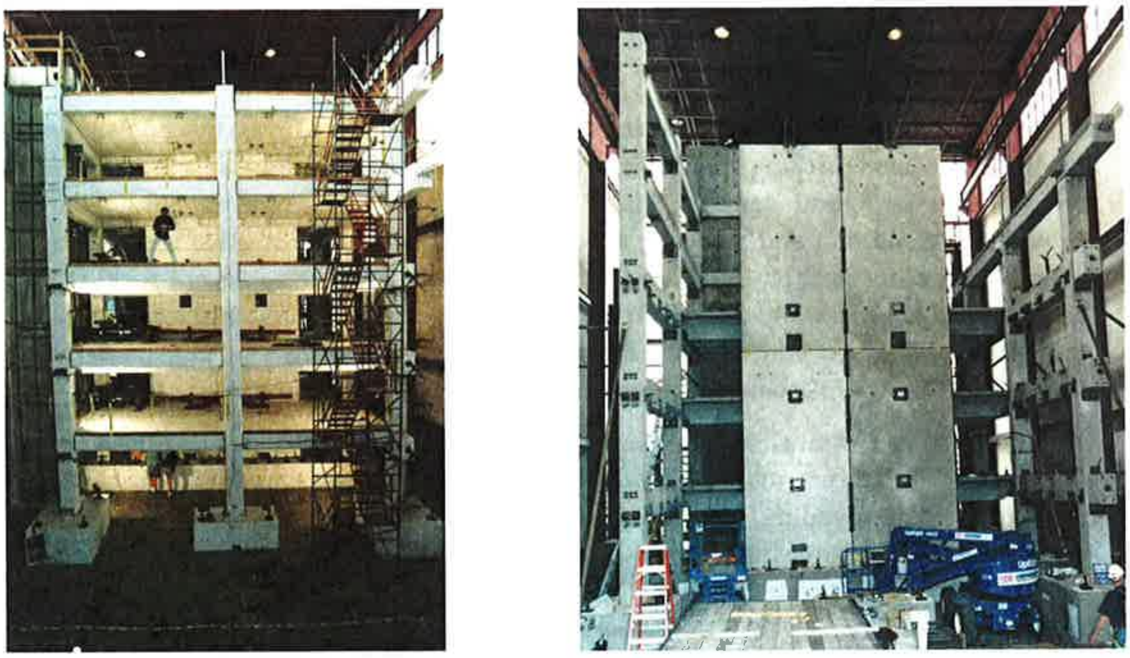


Figure 7.1. Five-Storey PRESSS Building tested at University of California, San Diego (Priestley et al., 1999).

In case of earthquake shaking, the inelastic demand is accommodated within the connection itself (beam-column, column-to-foundation or wall-to-foundation interface), through the opening and closing of existing gaps in a rocking motion. The gap opening or rocking acts as a fuse or isolation system with no damage accumulating in the main structural elements which are basically maintained in the elastic range. The basic structural skeleton of the building can thus remain undamaged after a major earthquake without any need for structural repair.

This is a major improvement when compared to cast-in-situ reinforced concrete solutions where, as mentioned, damage is expected to occur in the plastic hinge regions, leading to substantial costs of repairing and major business interruption.

7.2 The Hybrid System: Concept and Mechanism

A particularly promising and efficient solution within the family of jointed ductile connections is given by the "hybrid" system (Stanton et al. 1997, Fig. 7.2), where the connection reinforcement is given by the combination of unbonded post-tensioned bars or tendons and non-pre-stressed mild steel (or similarly additional external energy dissipation devices as discussed in the previous sections), inserted in corrugated metallic ducts and grouted to achieve fully bonded conditions.

Under static loading considerations (no seismic actions), these two types of reinforcement can guarantee a high level of connection strength and stiffness, with reduced congestion of the joint-connection region and easy installation process. Clearly, as for any structural system relying upon a moment resisting connection at the beam-column interface and taking advantage of the benefits of pre-stressing, longer span lengths can be achieved with reduced beam depths.

Under wind loading and low-seismic actions the clamping action of the post-tensioned bars/tendons guarantee a very stiff initial condition (gross section) when compared to a typical cast-in-situ solutions (cracked sections), thus resulting into immediate benefits under serviceability loading conditions.

Under moderate to high seismic actions, the traditional plastic hinge mechanism is replaced by this controlled rocking mechanism (gap-opening and closing) at the critical interface without any structural damage (Fig. 7.3) in the structural elements. While the tendons provide self-centering and restoring actions, the mild steel bars or other similar devices (for example coupling steel bars or U-shaped flexural plates between adjacent rocking walls) act as energy dissipaters and shock absorbers for the structure under seismic loading. This particular dissipative and re-centering mechanism is described by "flag-shape" hysteresis behaviour (force-displacement or moment-rotation cyclic behaviour).

A damage-control limit state can thus be achieved under a design level earthquake (typically that set at a 500 years return period, refer to Performance Objective Matrix described in paragraph 3.1.2) leading to an intrinsically high-performance seismic system almost regardless of the seismic intensity .

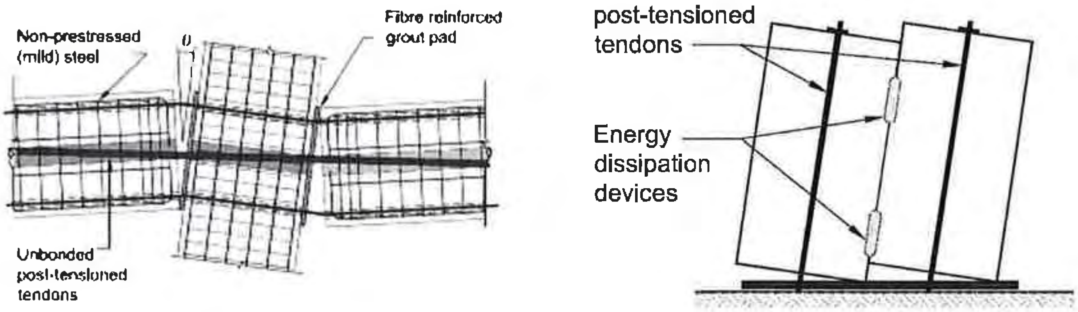


Figure 7.2. Jointed precast "hybrid" frame and wall systems developed in the PRESSS-Program (modified from fib, 2003; NZS3101:2006).

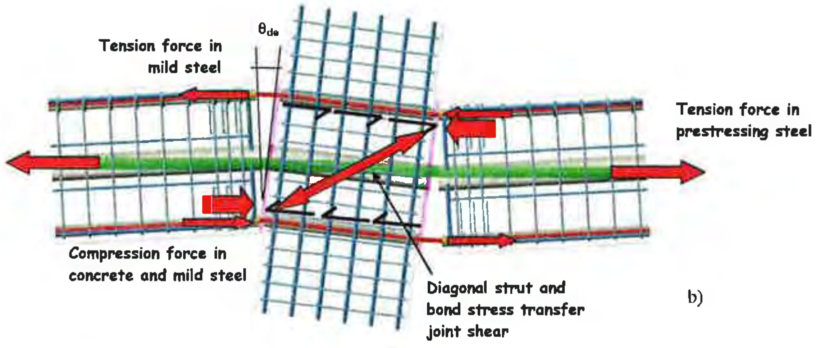


Figure 7.3. Hybrid beam-column connection: controlled rocking mechanism (courtesy of Mrs. Suzanne Nakaki).

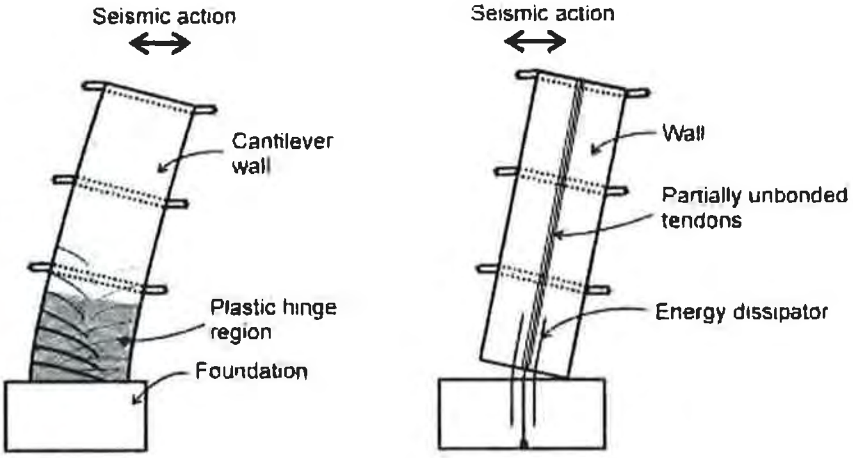


Figure 7.4. Comparison of monolithic wall and jointed precast rocking wall (after fib, 2003).

For a lateral load resisting system of structural walls, Figure 7.4 shows the comparative response of a traditional monolithic wall system (damage in the plastic hinge) and a jointed precast rocking wall solution (no damage and negligible residual deformations).

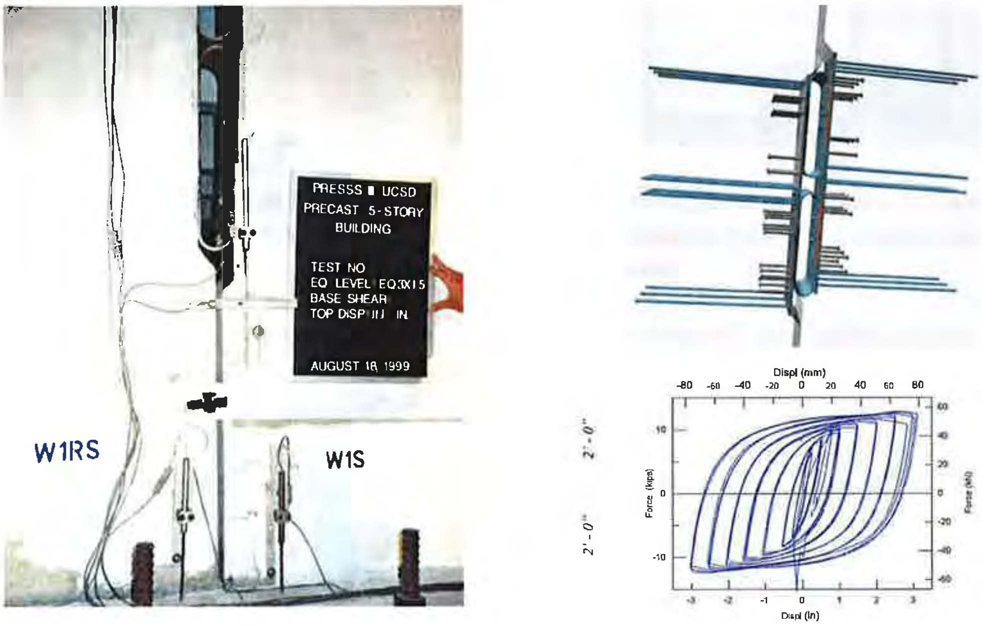


Figure 7.5. Rolling displacement behaviour of U-shape Flexural Plate Dissipaters between rocking walls

7.3 Replaceable Fuses – External Plug & Play Dissipaters

Following the declared target of a no-damage structural system (or at least a very low-damage system), significant effort has been dedicated in the past few years at the University of Canterbury to the development of cost-efficient externally located (*"Plug & Play"*) dissipaters, which can be easily demounted and replaced after an earthquake event, if required (Pampanin, 2005). This option allows a modular system with replaceable sacrificial fuses at the rocking connection, acting as the "weakest link of the chain", according to capacity design principles. Figures 7.6, 7.7.

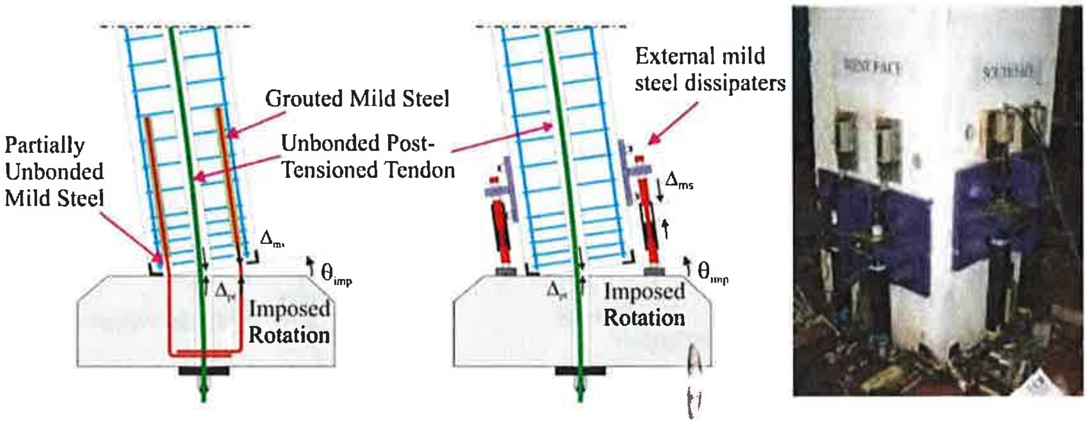
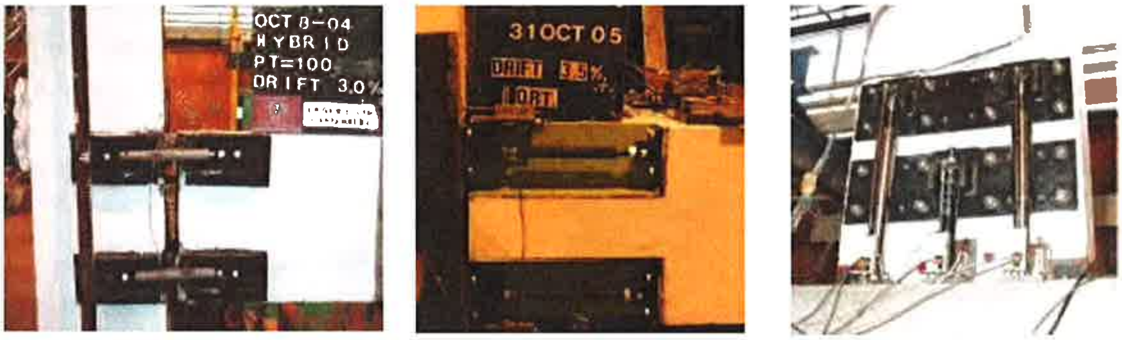


Figure 7.6. Internal versus external replaceable dissipaters at the base connections (after Marriott et al. 2008a).



(a) (b) (c)

Figure 7.7. Alternative configurations of external dissipaters for hybrid systems: (a) and (b) beam-column connections, with recesses in the beam (from Pampanin et al., 2006); (c) wall to foundation connection (from Marriott et al., 200b).

It is worth noting that the controlled rocking mechanism used in PRESSS-technology can be further improved by merging the advantages of the best energy dissipation and supplemental damping devices options. In terms of material and type of dissipation, either metallic or other advanced materials (e.g., shape memory alloys or visco-elastic systems) can be used to provide alternative dissipation mechanisms including elasto-plastic axial or flexural yielding, or friction devices.

7.4 Preventing Damage to Floors

As described in Chapter 5, there are several methods of avoiding the damage to slabs caused by frame elongation of rocking systems. The two principal methods are "articulated" floors or top-hinging beams.

7.4.1 Articulated floors

An "articulated" flooring system is built so that it is partially detached from the supporting structure, with sliding joints or other innovative details, to avoid damage to the floor but to retain the essential diaphragm action.

According to this proposed solution, the floor is connected to the lateral beams by slider/shear mechanical connectors, acting as shear keys when the floor moves (relatively) in the direction orthogonal to the beam and as sliders when the floor moves in the direction parallel to the beam. In theory, the system is able to accommodate the displacement incompatibility between floor and frame by creating an articulated or jointed mechanism, which is effectively decoupled in the two directions. A similar solution was used in the five-storey PRESSS building tested at the University of California, San Diego in 1999 (Priestley et al., 1993) in the form of welded X-plate mechanical connectors (shown in Fig. 7.8) between the double-tee floor members and the frame beams. See Pampanin et al., (2006) andAmaris et al., (2007) for more details of possible articulated flooring systems, including the possible system illustrated in Figure 7.9.

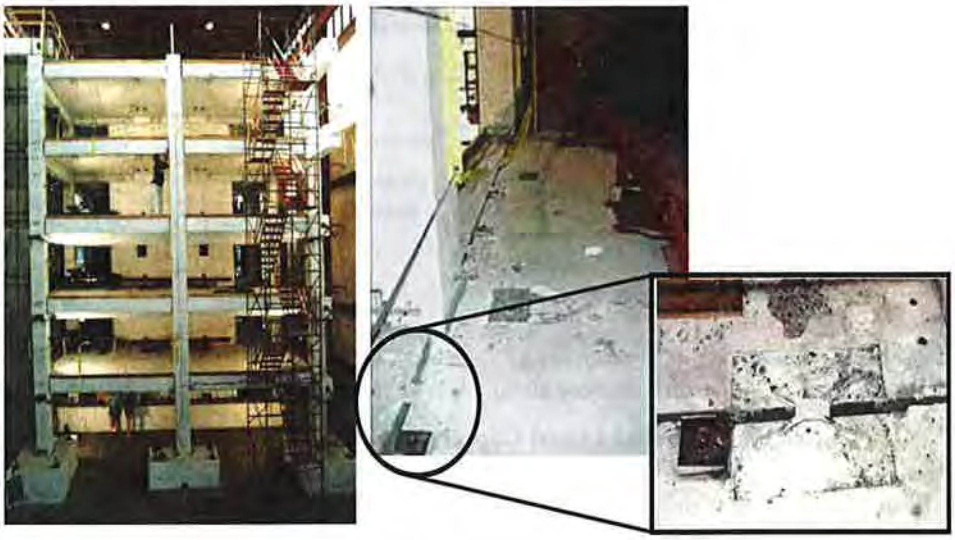
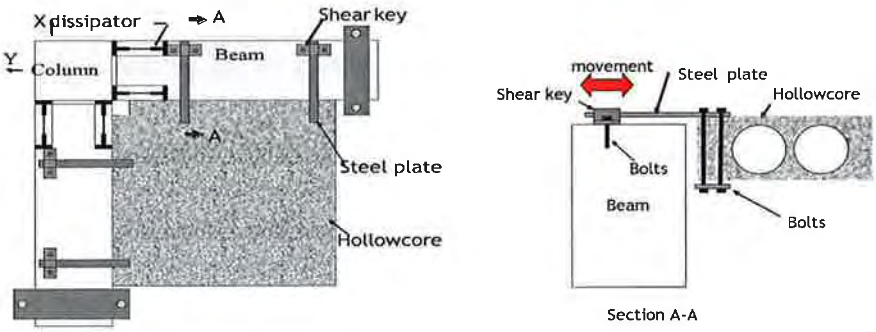


Figure 7.8. Discrete X-plate mechanical connectors used in the PRESSS five storey test building at San Diego (after Priestley et al., 1999).



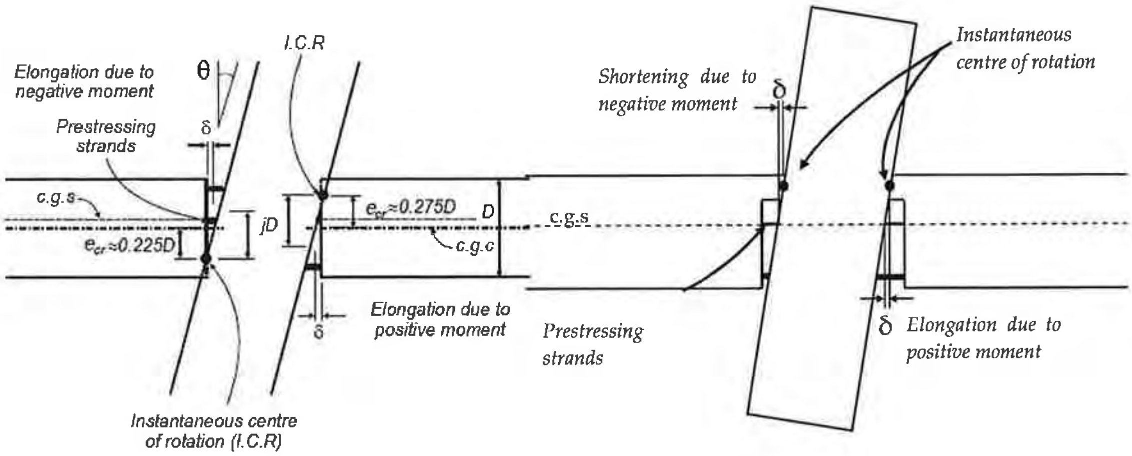
(a) Plan view. **(b) cross section at edge of slab.**

Figure 7.9. Beam-column joint with articulated floor unit at a corner of a reinforced concrete frame building (Amaris et al., 2007).

Another design option which will minimise floor damage is to use a combination of walls and frames to resist lateral loads, with walls in one directions and frames in the other. If the precast one-way floors run parallel to the walls and orthogonal to the frame, the elongation effects of the frame are minimised. This can be combined with partial de-bonding of the reinforcing bars in the concrete topping, and a thin cast-in-situ slab in the critical areas, to further increase the deformation compatibility.

7.4.2 Top-hinging beams

An alternative method of preventing damage to floors due to frame elongation is to design the beam to column connections such that there is a top hinge at the beam to column connection, which will allow some ductile rotation without causing damage to the slab. One variation of this is the "slotted beam" detail where a reinforced concrete beam has a slot formed into the lower half of the beam. This is shown in its simplest form in Figure 7.10.



(a) Interior plastic hinge lever arms for a conventional connection (Lindsay 2004).

(b) Interior plastic hinge lever arms for a non-tearing connection

Figure 7.10. Comparison of (a) Gapping connection and (b) Top-hinge solution.

The development of this concept starts from the evolution of the Tension-Compression Yield–Gap connection (TCY-Gap), developed during the PRESSS-Program, using mild-steel bars on the top (inserted into grouted sleeves) and unbonded post-tensioned tendons at the bottom. The peculiarity of this system was that beams and columns were separated by a small gap, partially grouted at the bottom to avoid the primary beam-elongation effects, thus not affecting the centre-to-centre distance between columns. However, such a solution would not prevent the tearing action in the floor due to the opening of the gap at the top of the beam, and no re-centering contribution is provided by the tendons, which are located with a straight profile in the centre of the compression grout and are thus not elongating.

An intermediate improved version would consist of an "inverted" TCY-Gap solution based on a single top hinge with the gap and the grouted internal mild steel bars placed in the bottom part of the beam. This modification, as per the "slotted beam" connection proposed by Ohkubo and Hamamoto (2004), for cast-in-situ frames (without post-tensioning), would succeed in preventing both elongation and tearing effects in the floor, but would not yet be capable of providing re-centring due to the location and straight profile of the tendons.

A further conceptual evolution has led to the development of the "non-tearing floor" beam-column connection developed and tested at the University of Canterbury (Amaris et al., 2007), which could be combined with any traditional floor system. Solutions are available with or without post-tensioning, providing an alternative "non-tearing" floor system able to exploit the advantages of the PRESSS-technology while still relying on more traditional floor-to-frame connections (i.e., topping and continuous starter bars). See Figure 7.11 for more details of alternative seating details for top-hung beam-column joint mechanisms.

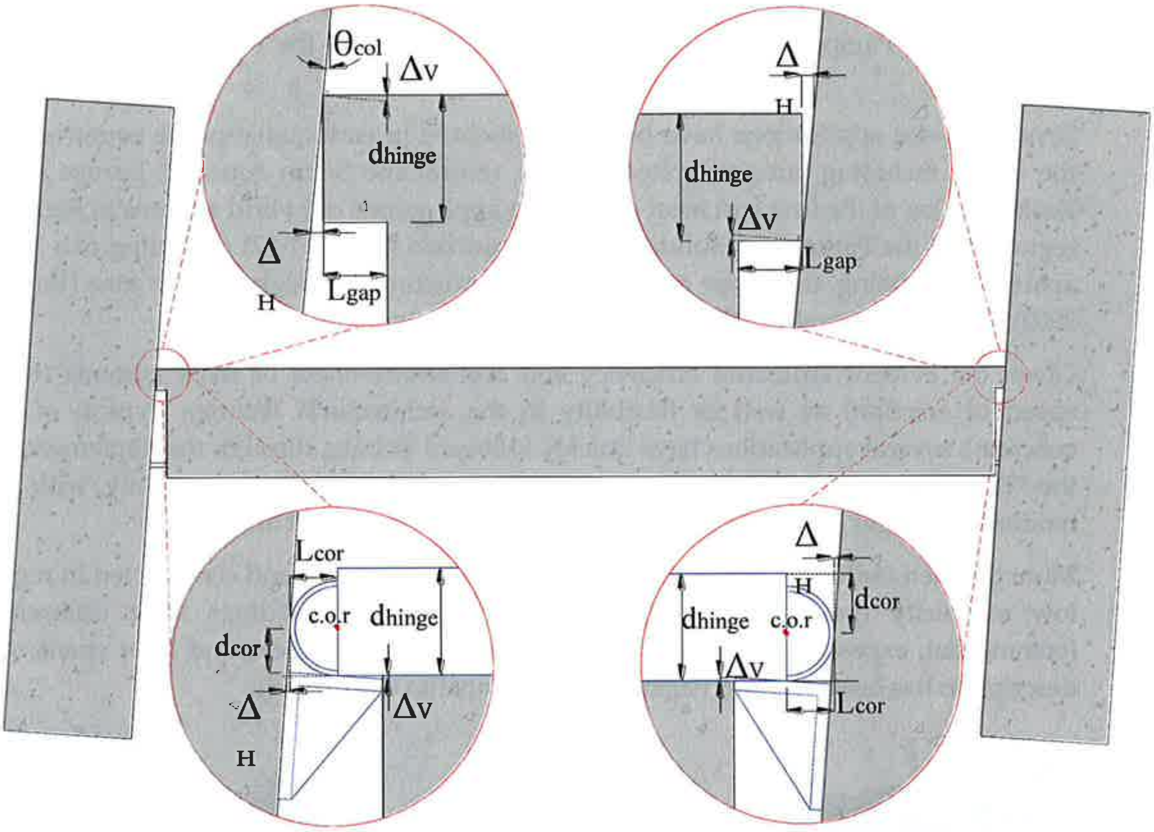


Figure 7.11. Deformation components of rectangular and circular hinge profiles under opening and closing rotations. Leslie, B., Bull, D., Pampanin, S. 2009

7.5 Examples of On-Site Implementations of PRESSS-Technology

Several on site applications of PRESSS-technology systems based on jointed ductile connections have been implemented in several earthquake-prone countries around the world.

The continuous and rapid development of jointed ductile connections using PRESSS-technology for seismic resisting systems has resulted, in only one decade, in a wide range of alternative arrangements currently available to designers and contractors for practical applications, and to be selected on a case-by-case basis (following cost-benefit analysis).

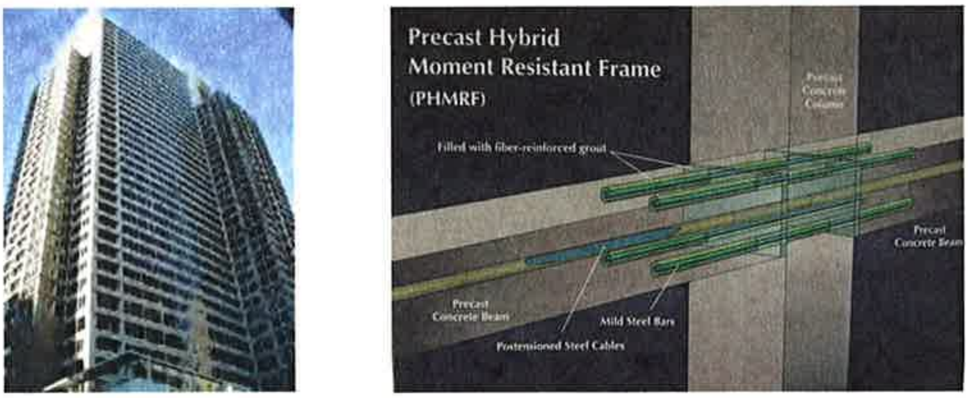


Figure 7.12. 39-storey Paramount Building, San Francisco (Englerkirk, 2002, photos courtesy of Pankow Builders, E. Miranda, Len McSaveney).

An overview of such developments, design criteria and examples of implementations have been given in Pampanin et al., (2005) and more recently in the PRESSS Design Handbook (2010)

Several on site applications have been implemented in earthquake-prone countries around the world, including but not limited to USA, central and South America, Europe and New Zealand. One of the first and most glamorous applications of hybrid systems in high seismic regions was the Paramount Building in San Francisco (Figure 7.12) consisting of a 39-storey apartment building, the tallest precast concrete structure in a high seismic zone (Englerkirk, 2002). Perimeter seismic PRESSS frames were used in both directions.

Given the evident structural efficiency and cost-effectiveness of these systems (e.g. high speed of erection) as well as flexibility in the architectural features (typical of precast concrete), several applications have quickly followed in Italy, through the implementation of the "Brooklyn System" (Figure 7.13), developed by BS Italia, Bergamo, Italy, with draped tendons for longer spans and a hidden steel corbel (Pampanin et al., 2004).

More than ten buildings, up to six storeys, have been designed and constructed in regions of low seismicity (gravity-load dominated frames). These buildings have different uses (commercial, exposition, industrial, hospital), plan configurations, and floor spans. A brief description has been given in Pagani (2002), Pampanin et al. (2004).

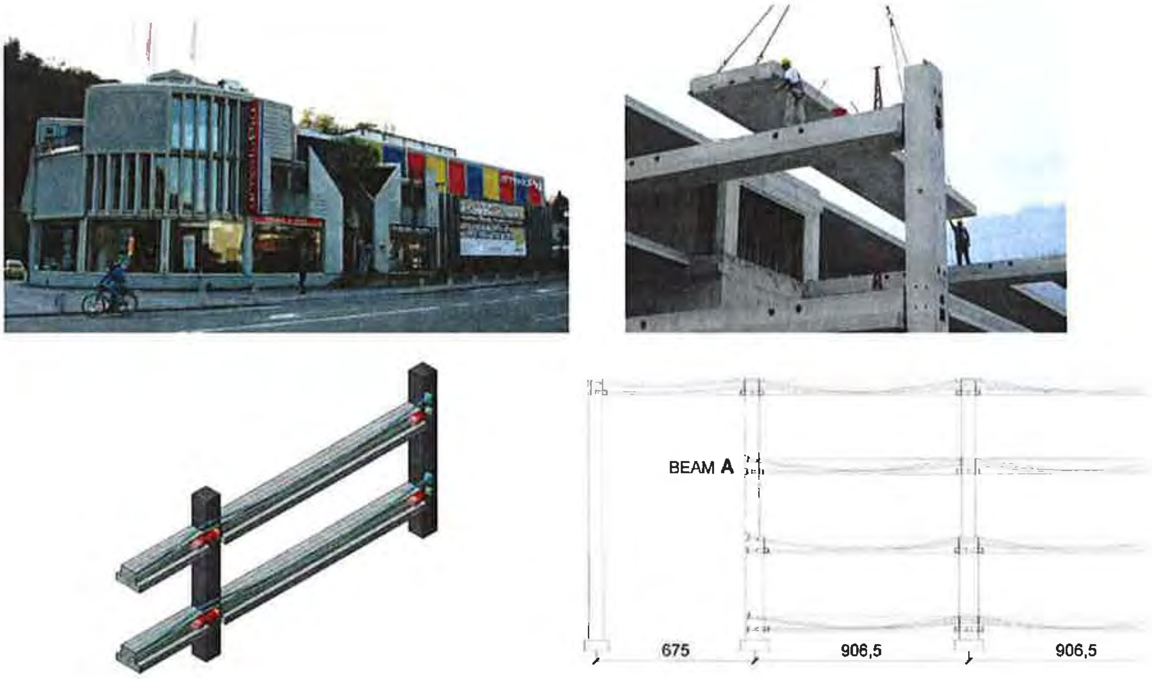


Figure 7.13. Photographs and sketches of the post-tensioned "Brooklyn System" (Pampanin et al., 2004).

Alan MacDiarmid Building, Wellington

The first multi-storey PRESSS-building in New Zealand is the Alan MacDiarmid Building at Victoria University of Wellington (Figure 7.14), designed by Dunning Thornton Consulting Ltd. The building has post-tensioned seismic frames in one direction and coupled post-tensioned walls in the other direction, with straight unbonded post-tensioned tendons. This building features some of the latest technical solutions previously described, such as the external replaceable dissipaters in the moment-resisting frame and unbonded post-tensioned sandwich walls coupled by slender coupling beams yielding in flexure (Cattanach and Pampanin, 2008). This building was awarded the NZ Concrete Society's Supreme Award in 2009.

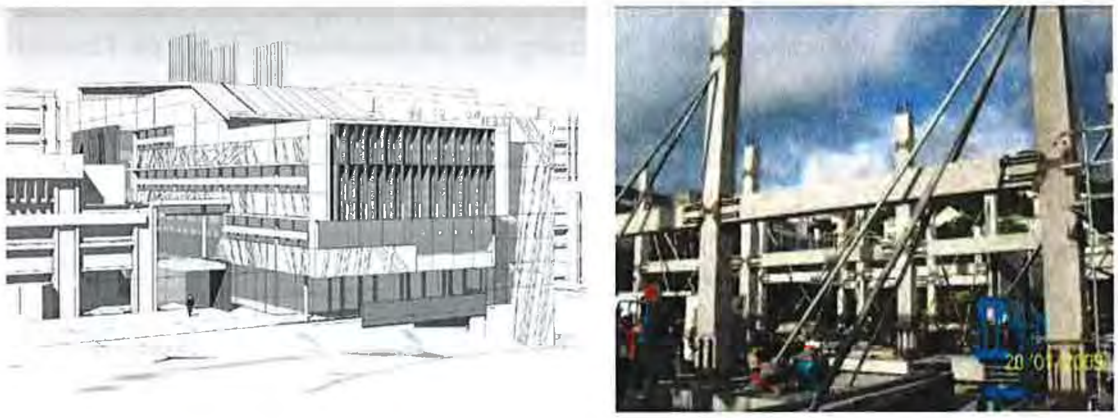
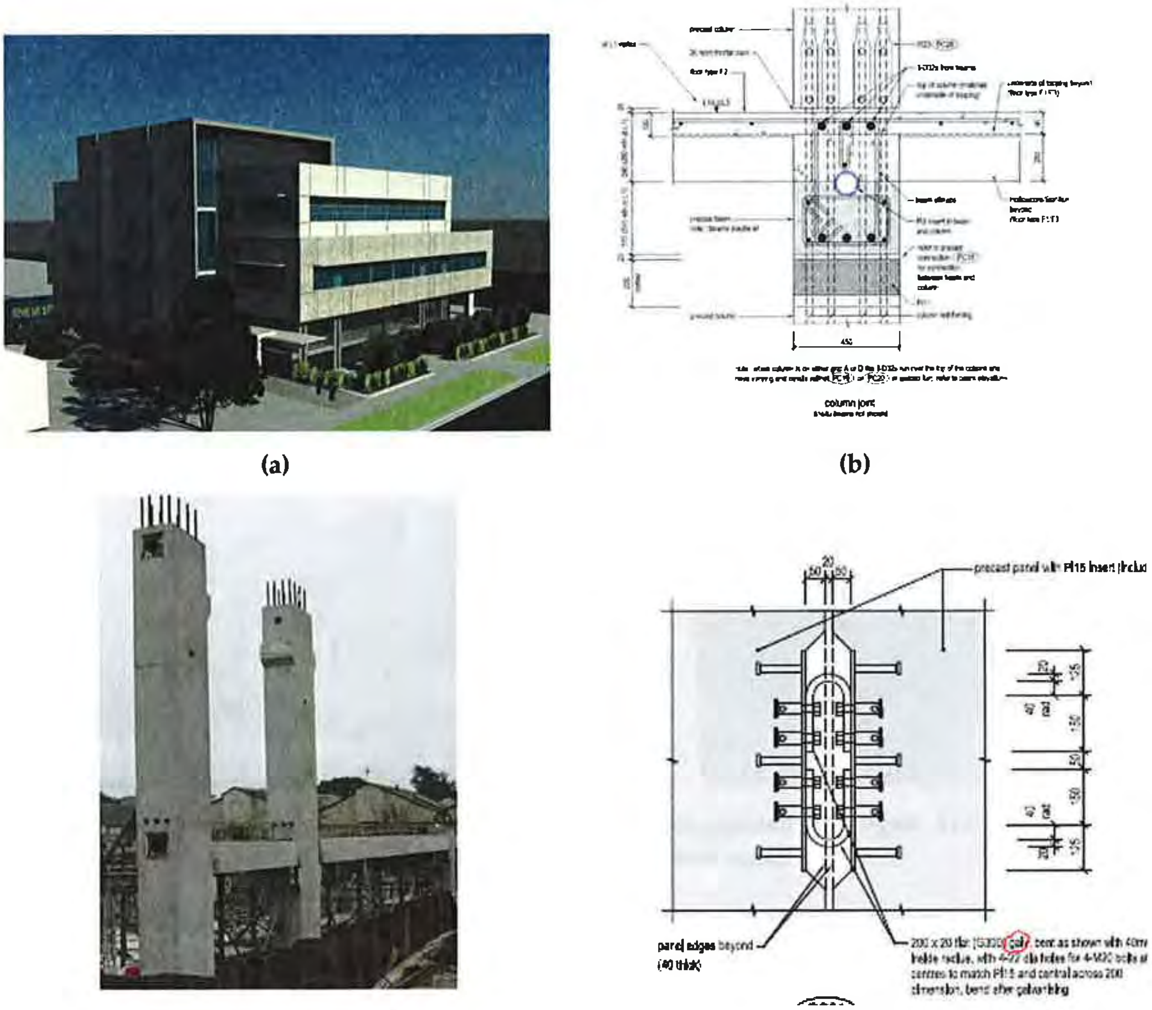


Figure 7.14. First multi-storey PRESSS-Building in New Zealand (Cattanach and Pampanin, 2008).

Southern Cross Hospital, Christchurch



(a)

(b)

(c)

(d)

Figure 7.15. Southern Cross Hospital, Christchurch (a) Finished building, (b) Beam-column detail,(c) Frame during construction, (d) dissipaters between coupled walls(Pampanin et al., 2011).

The design and construction of the second PRESSS-Building in New Zealand and the first in the South Island is the Endoscopy Consultants' Building in Christchurch, designed for Southern Cross Hospitals Ltd by Structex Metro Ltd (Figure 7.15). Again in this case both frames and coupled walls have been used in the two orthogonal directions. The unbonded post-tensioned walls are coupled by using the aforementioned U-Shape Flexural Plates dissipaters.

7.6 Testing of Seismic Performance in the Christchurch Earthquakes

Figure 7.16. Negligible damage, to both structural and non-structural components, in the Southern Cross Hospital after the earthquake of 22 February.

The Southern Cross hospital PRESSS-building has very satisfactorily passed the very severe tests of the two recent Christchurch earthquakes. The 22 February earthquake was very close to the hospital with a very high level of shaking.

As a comparison, Figure 7.16shows the minor/cosmetic level of damage sustained by the structural systems (post-tensioned hybrid frames in one directions with post-tensioned hybrid walls coupled with U-shape Flexural Plate Dissipaters) in the Southern Cross

Hospital Endoscopy Building. Furthermore, the medical theatres with very sophisticated and expensive machinery were basically operational the day after the earthquake.

One of the main feature in the design of a rocking-dissipative solution is in fact the possibility to tune the level of floor accelerations (not only drift) to protect both structural and non-structural elements including content and acceleration-sensitive equipment. More information on the design concept and performance criteria, modelling and analysis, construction and observed behaviour of the building can be found in Pampanin et al., (2011).

References

Amaris, A. Pampanin, S., Bull, D & Carr, A., (2007). Development of a Non-tearing Floor Solution for Jointed Precast Frame Systems. Proceedings of The New Zealand Society of Earthquake Engineering Annual Conference, Palmerston North, New Zealand.

Au, E., (2010). "The Mechanics and Design of a Non-tearing Floor Connection using Slotted Reinforced Concrete Beams", ME Thesis (2010), Department of Civil and Natural Resources Engineering, University of Canterbury Christchurch, New Zealand.

Bradley B. A., Dhakal, R. P., Mander J. B., and Li L., (2008). "Experimental multi-level seismic performance assessment of 3D RC frame designed for damage avoidance". *Earthquake Engineering and Structural Dynamics*, Vol. 37, No. 1, pp. 1-20.

Cattanach A., and Pampanin, S., (2008). "21st Century Precast: the Detailing and Manufacture of NZ's First Multi-Storey PRESSS-Building", NZ Concrete Industry Conference, Rotorua

Englerkirk, R., (2002). "Design-Construction of the Paramount – a 39 story Precast Prestressed Concrete apartment Building" PCI Journal, Vol. 47, No. 4

fib, (2003). International Federation for Structural Concrete, 2003. Seismic Design of Precast Concrete Building Structures, Bulletin 27, Lausanne, 254 pp

Kam, W.Y., Pampanin, S., (2011). " General Performance of Buildings in Christchurch CDB after the 22 Feb 2011 Earthquake: a Contextual Report", Department of Civil and Natural Resources Engineering, University of Canterbury

Leslie, B.J., Bull, D.K. & Pampanin, S., (2010). "The Seismic Performance of a Non-Tearing Floor Precast Concrete Structural System", in *Proceedings, New Zealand Society for Earthquake Engineering Conference*, Wellington, New Zealand, 2010.

Li L., Mander J. B., and Dhakal R. P., (2008). "Bi-directional cyclic loading experiment on a 3-D beam-column joint designed for damage avoidance". *ASCE Journal of Structural Engineering*, Vol. 134, No. 11, pp. 1733-1742.

Lindsay, R., (2004). "Experiments on The Seismic Performance of Hollow-Core Floor Systems in Precast Concrete Buildings", ME Thesis (2004), Department of Civil and Natural Resources Engineering, University of Canterbury Christchurch, New Zealand.

Marriott, D., Pampanin, S. , Bull, D., Palermo A., (2008). "Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems with Alternative Dissipating Solutions", *Bulletin of NZ Society for Earthquake Engineering*, Vol. 41(2), 90-103

NZCS, (2010). " PRESSS Design Handbook" (Editor: S. Pampanin), New Zealand Concrete Society, March

NZS 3101, (2006). "Appendix B: Special Provisions for the Seismic Design of Ductile Jointed Precast Concrete Structural Systems" Standards New Zealand, Wellington.

Ohkubo, M., and Hamamoto, T., (2004). "Developing Reinforced Concrete Slotted Beam Structures to Reduce Earthquake Damage and to Enhance Seismic Structural Performance." 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada.

Pampanin, S., Amaris, A. and Palermo, A., (2006).Implementation and Testing of Advanced Solutions for Jointed Ductile Seismic Resisting Frames.FédérationInternationale du Béton - Proceedings of the 2nd International Congress, June 5-8, 2006 – Naples, Italy.

Pampanin S., (2005). Emerging Solutions for High Seismic Performance of Precast - Prestressed Concrete Buildings, Journal of Advanced Concrete Technology (ACT), invited paper, Vol. 3 (2), pp. 202-222.

Pampanin, (2010). "Damage-control self-centering structures: from laboratory testing to on-site applications", Series "Geotechnical, Geological, and Earthquake Engineering, Volume 13"; Chapter 28 in the book "Advancements in Performance-Based Earthquake Engineering (M Fardis Editor) Publisher Springer, ISBN: 978-90-481-8745-4 (Print) 978-90-481-8746-1 (Online), Part 3, pp. 297-308

Pampanin, S., Kam W., Haverland, G., Gardiner, S., (2011). Expectation Meets Reality: Seismic Performance of Post-Tensioned Precast Concrete Southern Cross Endoscopy Building During the 22nd Feb 2011 Christchurch Earthquake" NZ Concrete Industry Conference, Rotorua, August

Pampanin, S., Pagani, C., Zambelli, S., (2004). "Cable Stayed and Suspended Solution for Precast Concrete Frames: the Brooklyn System", Proceedings of the New Zealand Concrete Industry Conference, Queenstown, New Zealand, September 16-18.

Priestley, M. J. N., Sritharan, S., Conley, J. R. and Pampanin, S., (1999). "Preliminary results and conclusions from the PRESSS five-story precast concrete test building." PCI Journal, 44(6), 42-67.