6 NEW FORMS OF DAMAGE-RESISTANT STRUCTURE

Damage-resistant design is the newest way of limiting damage in a major earthquake, whereby damage-resistant structures can be designed to absorb energy in a major earthquake, rocking back to an undamaged position after the shaking. This combines ductility to reduce the design forces with little or no residual damage. New Zealand engineers are contributing to international developments in this field, as described in the following chapters. Experimental research at the University of Canterbury has supported these developments, which will allow new damage-resistant buildings to be built at no more cost than conventional designs.

6.1 Rocking controlled dissipative rocking or hybrid concept

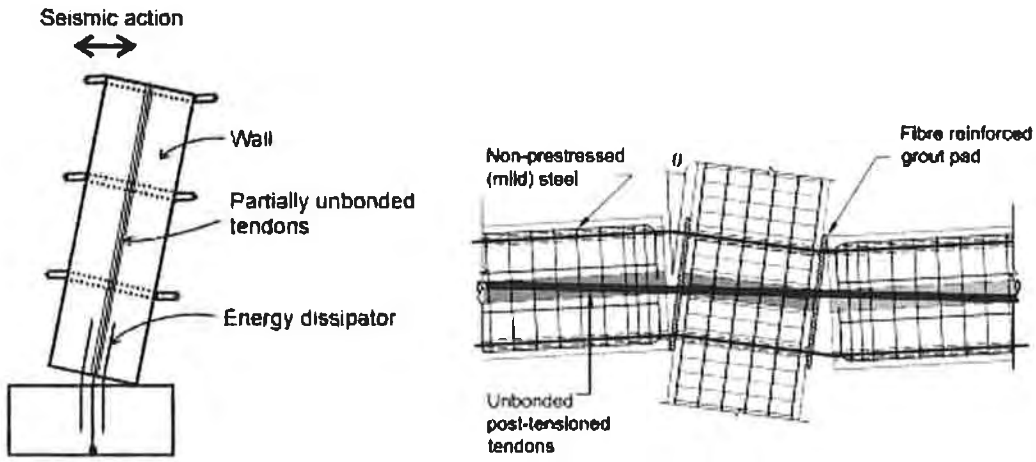
The main type of damage-resistant design is to use one or more of many new rocking structural systems being developed, in concrete, steel, timber, or mixed materials. The introduction of jointed ductile systems, assembled by unbonded post-tensioning and able to undergo severe seismic events with minor structural damage, represents a major development in seismic engineering.

The conceptual innovation of "capacity design" introduced by professors Park and Paulay in the 1960s and 1970s is universally recognised as a major milestone in the development of earthquake engineering, and of seismic design philosophies in particular. Similarly, the concept of ductile connections able to accommodate high inelastic demand without suffering extensive material damage, developed in the 1990s, is the next development in high-performance damage-resistant structural systems.

This revolutionary technological solution and the associated conceptual design philosophy was developed in the 1990s as an outcome of the U.S. PRESSS Program (PREcast Seismic Structural System) coordinated by the University of California, San Diego (Priestley et al. 1999) . The main goal of the project was to create innovative damage-resistant solutions for precast concrete buildings, as an alternative to the traditional connections based on cast-in-situ concrete. High-performance, low-damage structural systems for both frames and walls were developed through the use of dry jointed ductile connections, where prefabricated elements are joined together by means of unbonded post-tensioned tendons. A wall system is shown in Figure 6.1(a) and part of a frame system in Figure 6.1(b).

During the seismic response, the articulated or segmented elements are subjected to a controlled rocking mechanism. After the earthquake shaking, due to the elastic clamping action of the unbonded tendons the structure returns back to the original position, with negligible damage and negligible residual deformation. Additional energy dissipation capability can be provided by means of grouted mild steel bars or other supplemental damping devices to create a "hybrid" system (Stanton et al., 1997) which combines re-centering capability with energy absorption, resulting in particular "flag-shaped" hysteresis behaviour, to be described later, as shown in Figure 6.2.

This type of damage-resistant structural system has been further developed for concrete, steel, and timber structures as described in the following chapters.



(a) Rocking wall system.

(b) Beam-column joint in a rocking frame system.

Figure 6.1. Rocking hybrid frame or wall system (after fib, 2003).

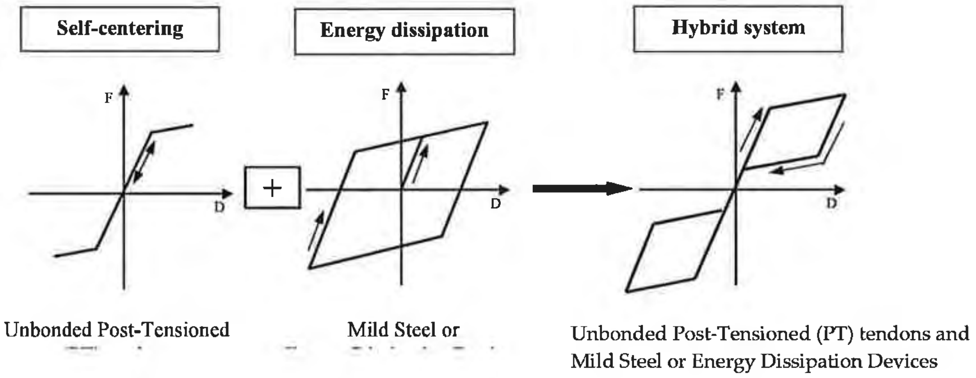


Figure 6.2. "Flag-shape" hysteresis loops for a hybrid frame or wall system (after fib, 2003).

6.1.1 Ancient Technology

In a fascinating way, buildings with rocking walls represent a clear example of modern technology based on our ancient heritage. We could in fact clearly recognise the lessons and inspiration provided by the long-lasting earthquake resisting solutions in the ancient Greek and Roman temples consisting of segmental construction with marble blocks "rocking" on the top of each other under the lateral sway.

Figure 6.3. Earlier implementation of a self-centering limited-damage rocking system, for earthquake loading (Dionysus temple in Athens).

The weight of the blocks themselves and the heavy roof-beams provided the required "clamping" and re-centering vertical force (Figure 7.17). The shear force between the elements was transferred by shear keys, made of cast lead, preventing the occurrence of sliding and also probably acting as relocating pivot points.
Exemples of concrete and timber buildings wall system are presented in Chapters 7 and 9.

6.2 Rocking Wall and Rocking Frame Systems

The most simple form of rocking damage-resistant structural elements are rocking walls. Rocking precast concrete walls will be described in Chapter 7 and rocking timber walls in Chapter 9. Multiple walls can be used with damping devices inserted between the walls, as described in Chapters 7 and 9. A similar system can be used with rocking braced frames in steel structures, as described in Chapter 8.

Rocking frame systems have similar overall performance to rocking wall systems, with the same flag shape loops shown in Figure 6.1, but there are many more points of gap opening throughout the building, and potential for so careful detailing is required to make sure that the whole structural system performs as intended with no significant damage, especially to floors, as described below. Several techniques for managing this issue for steel structures are described in Chapter 8.

Some buildings may have mixed wall and frame systems, with walls resisting lateral loads in one direction and frames in the orthogonal direction.

6.3 Avoiding Damage to Floors

In addition to protecting the structural skeleton from damage, one of the largest problems to be overcome in earthquake resistant structural systems is potential damage to floors .Most of the standards and codes around the world allow the use of design forces that are generally smaller than those required for elastic response, providing that the critical regions of the structure have adequate ductility and energy dissipation capacity. Such approaches are fundamentally based on a casualty-prevention principle, where structural damage is accepted providing that collapse is avoided. Designers must select a proper mechanism of plastic deformation and use capacity design principles to ensure that the chosen mechanism can be developed.

Both conventional frames and rocking beam-column systems can cause gaps to form between to floor and the neighbouring beams. The mechanisms that cause the gapping are described below. This gapping disrupts the flow of forces across the floors to the supporting frames and, in extreme cases, can reduce the support of the floor to where the floor drops off the supporting beams.

The most likely cause of floor damage is frame elongation, described below. New techniques are being developed for the design of non-tearing floors which can remain undamaged after a rocking structure deforms and returns to its original position after a major earthquake, as described later. This is also a problem for conventional cast-in-place reinforced concrete buildings where plastic hinges cause frame elongation.

6.3.1 Floor diaphragms

In many multi storey buildings, the bulk of the weight of the building is in the concrete floor slabs, so the largest inertial forces arising during an earthquake are forces in the floors. To resist these forces, it is essential that the floor diaphragms remain undamaged, even during major earthquakes.

In-plane diaphragm action of floors is exceedingly important for the lateral load resistance of multi storey buildings. The floor diaphragm is a critical structural element which holds the building together, and transfers lateral loads from the floor or elsewhere in the building into the lateral load resisting system of frames, walls or braces. Damage to a floor diaphragm can compromise the structural performance of the whole building. Floor diaphragms must always be carefully designed for the high in-plane forces which are obtained from analysis of the whole structure. The diaphragm forces are much larger in floors with openings, or in irregular buildings, especially if there is a change in the lateral load resisting system with storey height, or if the building has a number of different lateral load resisting systems.

The development of forces that cross the floors (in diaphragm action) during earthquakes is due to firstly, the mass of the floor and contents on that floor being accelerated by the earthquake motions and secondly, the various vertical structures (frames and walls) that resist the horizontal displacements of the earthquake. If the vertical structures acted in isolation from each other, each would form an individual displaced shape under the lateral forces, but the floor diaphragms tie the vertical structures to each other they are hence forced to displace to a common shape. This can result in large forces forming across the floor diaphragms as the vertical structures of different stiffness and strengths are constrained to shapes that are not the same as if they were acting in isolation.

These "diaphragm forces" are significantly easier to design and detail for when the floors are still essentially intact and well connected to the supporting frames (and walls). This is one of the major advantages of the "non-tearing floor" over the conventional and rocking structure frame systems which produce large gaps or "tears' between the floors and neighbouring frames, as described later.

6.3.2 Seating of precast floors

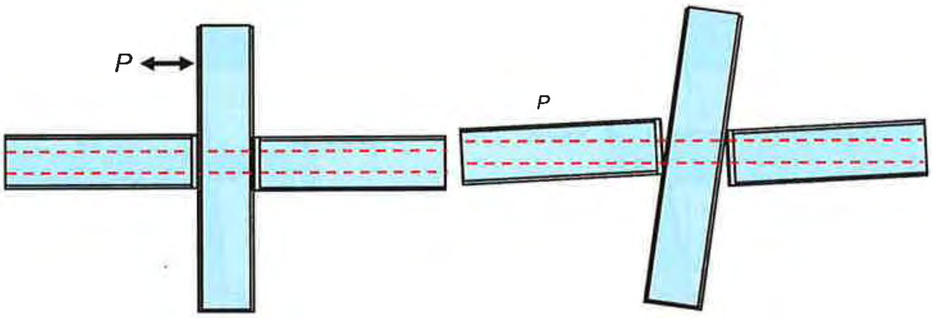
Another critical reason for avoiding damage to floors is the possible loss of gravity load seating for the floors. This can be a particular problem for one-way precast concrete floor systems. Any tearing of floors, especially at the supporting edge, can compromise occupant safety. Experimental tests on the 3-dimensional performance of precast concrete frames and hollow core floor units (Matthews et al., 2003), have further underlined issues related to the inherent displacement incompatibility between precast floors and lateral load resisting systems, including beam-elongation effects. Appropriate design criteria and detailed technical solutions should thus be adopted.

Other problems inherent with the use of precast concrete floor systems in earthquake regions have been identified (Park, Paulay, and Bull, 1997) including loss of support, analysis and design of diaphragms and their connections, transfer diaphragms, strut & tie node points, serviceability requirements and construction methods.

6.4 Frame Elongation

For traditional cast-in-place ductile frames in reinforced concrete, experimental and numerical studies (Fenwick and Fong, 1979, Douglas, 1992 and Fenwick and Megget, 1993) have shown that plastic beam hinges cause growth in the beam length, depending on the beam depth, the expected position of the neutral axis and the rotation (drift) demand. This frame elongation has been identified as a serious issue for reinforced concrete moment-resisting frame buildings, and much research has been done to try and alleviate the problem (Peng, 2009). This issue of frame elongation can also be a serious problem for a damage-resistant rocking system, as described below.

It has been argued (Pampanin, 2010) that frame elongation is less for a post-tensioned rocking frame than for a traditional cast-in-place reinforced concrete frame, because the rocking system has only geometric elongation and does not have a material contribution due to the cumulative residual strain within the steel of the plastic hinges. Frame elongation could also be less for a post-tensioned rocking frame if the beam depth is smaller than in a traditional system.



(a) At rest **(b) During lateral displacement**

Figure 6.4. Post-tensioned beam-column joint, showing frame elongation.

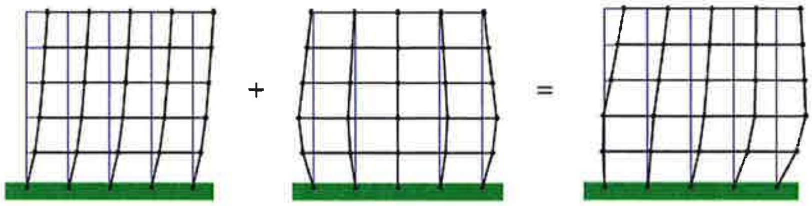
Tests of beam/column subassemblies with one column and without slabs have shown very good behaviour with no permanent displacements after the earthquake, and no significant damage. However, when the beam supports a slab, and/or when the beam is part of a frame that has more than one column, additional effects occur which may result in damage.

For frames with more than one column, the gaps which form at the beam ends cause "beam growth" or "frame elongation" (Peng, 2009). In conventional sway analysis, used in routine design, this effect is not considered as shown in Figure 6.5(a). The effect of the beam-growth itself is shown in Figure 6.5(b). It can be seen that the exterior columns are being pushed apart. The combined effect, which is the likely behaviour of an actual frame under significant seismic displacements, is shown in Figure 6.5(c). It can be seen that

i) As the number of bays in the seismic frame increases, the demands on the columns due to gap opening also increase. While this does not contribute toward the possibility of a soft-storey mechanism (as the columns are being pushed in different ways), there is more possibility that the capacities of some columns may be used up.

ii) The beams at the first storey are subject to compression forces. This will increase their flexural strength and increase the possibility of column yielding above that from conventional analysis.

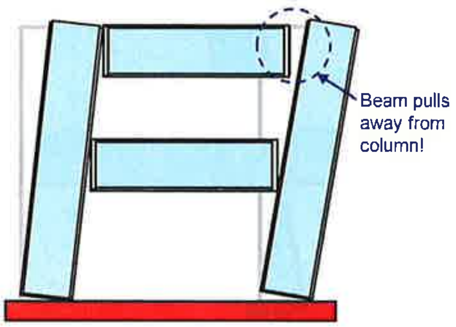
iii) The beams in other stories will be subject to axial forces too. Above the level of maximum frame expansion, they may well be in tension. This is illustrated in Figure 6.4. Here, if there are relatively stiff columns held in place at the base, the beams and columns will want to separate at the higher levels, and this should be taken into account in the structural analysis. In a worst-case scenario, this could lead to column failure as shown in Figure 6.5, unless properly designed for.



Sway (conventional analysis) Beam growth combined

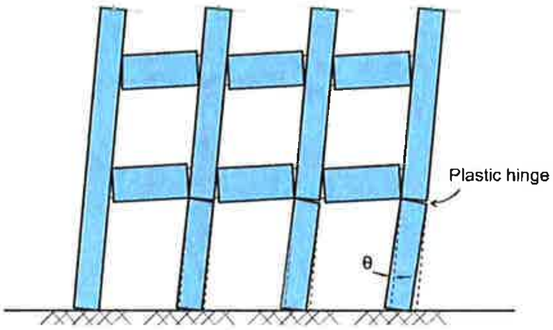
(a) (b) (c)

Figure 6.5. Frame elongation in moment-resisting frames (Kim et al., 2004).



(a)

Figure 6.6. (a) Gap Opening Effect on 2 Storey Frame with Stiff Columns (MacRae, 2010).



(b)

Figure 6.6. (b) Damage to column caused by frame elongation (Pampanin, 2010).

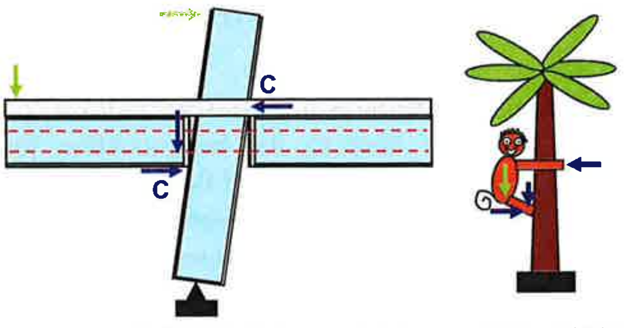
6.5 Non-Tearing Floors

For frames with slabs, where the slabs are connected to the beams, the gap opening at the end of the slab wants to cause extend the slab, as shown in Figure 6.7a). The forces applied on the joint may be understood using the idealisation in Figure 6.7(b), where the tension force in the concrete slab is equivalent to the force in the arms of the monkey. As stated above, it is essential to prevent any significant damage to the floor slabs, by designing some kind of non-tearing floor solution.

6.5.1 Damage to slabs

There are two possible situations:

a) If the slab is very strong in tension, then the gap can never open and the desired frame yielding mechanism cannot occur. This means that the moment demand from the beam and slab will be increased, and column yielding may occur unless the columns are specifically designed to resist these larger forces. Any serious column damage, such as shown in Figure 6.6, is not acceptable in a damage-resistant design.



(a) Deformation with a slab. **(b) Monkey Idealisation**

Figure 6.7. Slab Effects on Subassembly (from MacRae, 2010a).

b) If the slab is not strong enough in tension, then the gap can open. However, the gap opening will result in slab damage during the imposed displacements. This damage is also not acceptable in a damage-resistant design. Some damage from a test of this type, is shown in Figure 6.8.

Figure 6.8. Slab damage in a post-tensioned steel beam subassembly (Clifton, 2005).

6.5.2 Methods of avoiding slab damage

There are several methods of avoiding the damage to slabs caused by frame elongation described above. The two principal methods are to use "articulated" floors or top-hinging beams.

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. Possible details for articulated floors are given in Chapter 7 for concrete structures and Chapter 8 for steel structures, but there is continuing debate about their effectiveness. At this point in the development of damage-resistant buildings, there are aspects of emerging technologies that may require further research, and one is the divergence of opinion on how to progress and apply the variations of "articulated floor" systems.

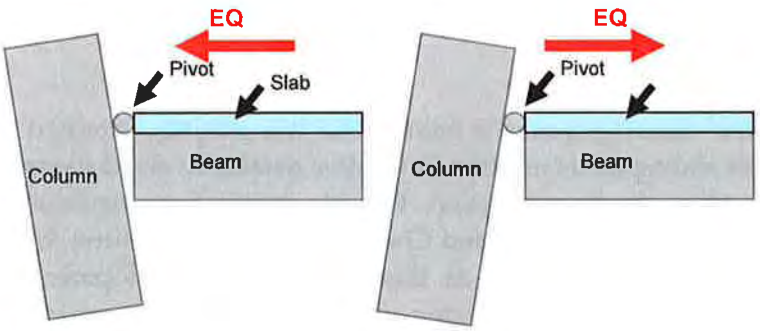
Top-hinging beams

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, which will allow 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, as described further in Chapter 7. A similar detail is the sliding hinge joint for steel structures described in Chapter 8.

The term "non-tearing floors" pertains to a beam-column-floor configuration that results in very small cracks in the floor next to the beam-column junctions. Typically, the configuration involves forming a hinge or pivot at floor level. A schematic of the floor pivot is shown in Figure 6.9. The slotted beam has conventional reinforcing bars crossing the slot between the beam and column, so it generates flexural strength in a similar manner to a conventional beam. Figure 6.10(a) shows how the slot opens as a designed gap, and the reinforcement crossing the slot can be seen. Figure 6.10(b) shows the cracks that form in conventional beams. It is evident that the amount of damage in the slotted beam/ "non-tearing floor" specimen is considerably less than that seen in the conventional reinforced concrete beam (at a lesser inter-storey drift). The comparative lower damage was mirrored in the floor slabs of the two test specimens.

The very minor cracking shown in Figure 6.10(a) is considerably less disruptive to the flow of forces across the floors than the beam cracking shown in Figure 6.10(b). The minor cracking in the top-hinging floor will typically allow buildings to be reoccupied immediately after a major earthquake, with no repair required. Recent studies for concrete beams, at the University of Canterbury by (Amaris, 2007), (Au, 2010) and (Leslie, 2010), have confirmed the technical viability of this method. Au and Leslie focused on a conventional reinforced slotted beam – see Figure 6.10(a), while Amaris developed a hybrid version of slotted beam, "non-tearing floor" that incorporated aspects of the PRESSS technology, including the ability to re-centre the buildings (because of post tensioning in the beams and gravity effects on rocking columns) as described in Chapter 7.

Frames with "non-tearing floor" connections can be married with rocking wall systems, with or without post tensioning and rocking structural steel braces, as described in Chapter 6. "Non-tearing floor" solutions have been developed for buildings primary frames or walls constructed with concrete, structural steel, or timber.



(a) Right to left earthquake movement. (b) Left to right earthquake movement.

Figure 6.9. Schematic of the pivot or hinge detail.

(a) (b)

Figure 6.10. (a) Slotted reinforced concrete beam after 4.5% peak drift (Au, 2010). (b) Damage to conventional beam after 3.0% peak drift (Lindsay, 2004).

References

Amaris, A., Pampanin, S., Bull, D. and 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.

Clifton, G.C., (2005). Semi-Rigid joints for moment resisting steel framed seismic resisting systems. PhD Thesis, Department of Civil and Environmental Engineering, University of Auckland.

Douglas, K.T., (1992). Elongation in Reinforced Concrete Frames. PhD Thesis, Department of Civil Engineering, University of Auckland.

Fenwick, R.C. and Megget, L.M., (1993). Elongation and Load Deflection Characteristics of Reinforced Concrete Members containing Plastic Hinges. Bulletin of the New Zealand National Society for Earthquake Engineering, 26 (1). 28-41.

Fenwick, R.C. and Fong, A., (1979). The Behaviour of reinforced concrete beams under cyclic loading , University of Auckland, School of Engineering, Auckland, New Zealand

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.

Matthews, J., Bull, D., and Mander J., (2003). Hollowcore floor slab performance following a severe earthquake. Concrete Structures in Seismic Regions. Proceeding of the First fib Symposium. Athens, Greece.

Pampanin, S., (2010). "Damage-control self-centering structures: from laboratory testing to on-site applications", Chapter 28 in "Advancements in Performance-Based Earthquake Engineering (M FardisEditor) Publisher Springer,Part 3, pp. 297-308

Park, R., Paulay, T. and Bull, D., (1997). "Seismic Design of Reinforced Concrete Structures", *Technical Report No. 20, New Zealand Concrete Society.* 1997, 135 pp

Peng, B., (2009). Seismic Performance Assessment of Precast Concrete Buildings with Precast Concrete Floor Systems. PhD Thesis, University of Canterbury.

Priestley, M.J.N., Calvi, G.M. and Kowalski, M.J. (2007). Displacement Based Seismic Design of Structures. IUSS Press, Italy.

Priestley, M.J.N. and MacRae, G.A., (1996). Seismic Tests of Precast Beam-to-Column Joint Sub-assemblages with Unbonded Tendons, PCI Journal, January-February; 64-80.

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.

Stanton, J.F., Stone, W.C., and Cheok, G.S., (1997). A hybrid reinforced precast frame for seismic regions, PCI Journal, Vol. 42, No.2, pp.20-32