SELF CENTERING SEISMIC RESISTANT SYSTEMS

INTRODUCTION

Self-centering systems are a new breed of earthquake resistant structural systems that aim at preventing damage to structural members during seismic loading. Traditionally seismic resistant systems have been composed of moment resisting joints which are designed to undergo plastic deformation during an earthquake. The retrofit of these damaged structural members can be very costly. Self-centering systems provide a mechanism which does not allow inelastic deformations therefore reducing the damage normally observed in structural members.

The main idea behind this new type of system is to allow certain joints throughout the structure to open and close during an earthquake. This opening and closing of joints is permitted by post-tensioned tendons which connect the different joints and remain elastic during a specified design earthquake. The restoring forces given by these tendons with the help of gravity loads provide the structure with a self-centering mechanism which keeps residual drifts to a minimum. In addition to the post-tensioned tendons energy dissipation elements are needed to provide nonlinear softening behavior and ductility. There are three main types of self-centering mechanisms: unbonded post-tensioned precast concrete walls, unbonded post-tensioned precast moment-resisting frames, steel moment resisting frames with post-tensioned connections, and unbonded post-tensioned bridge piers. A detailed description of these applications and their advantages is presented ahead.

APPLICATIONS

- ***Unbonded Post-Tensioned Precast Concrete Walls***
  This system is composed of precast concrete walls placed directly on top of each other with a post-tensioned tendon running vertically through them. The steel tendon is unbonded with respect to the wall, and is anchored at the foundation and the top of the wall. Spiral reinforcing steel is used in the wall panels near the base of the wall to provide confinement. This concept can be seen in Figure 1. During an earthquake the structure will sway and the wall joints will open and eventually close due to the restoring forces as observed in Figure 1.

Figure 1. Unbonded Post-Tensioned Precast Concrete Walls

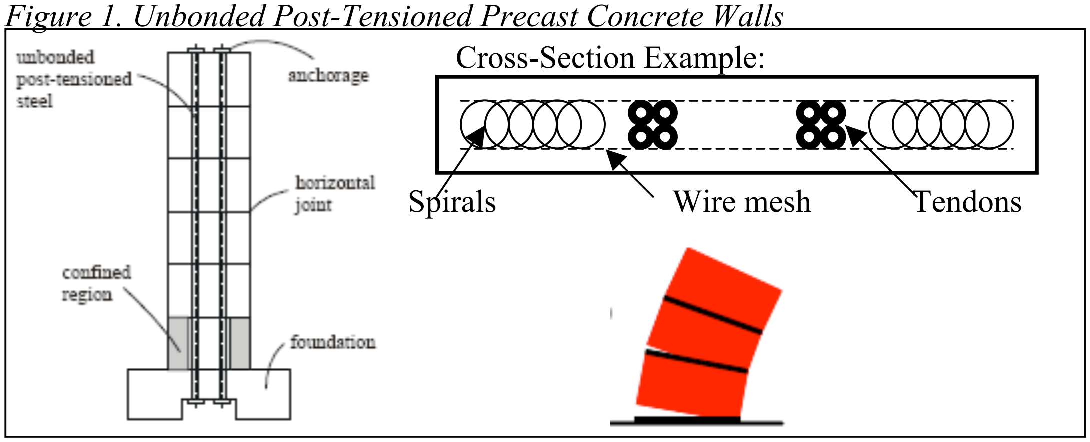
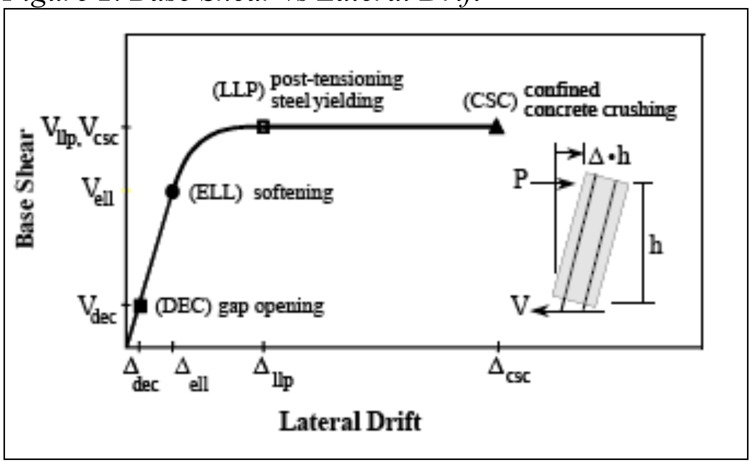


Figure 2 shows what would occur in this type of sytem when base shear reaches certain values as a function of lateral drift. The first point in the figure belongs to the initial stage of decompression (gap opening) at the horizontal joint in the foundation. The decompression marks the beginning of non-linear behavior due to opening of gaps. At the second point the structure is starting to loose some lateral stiffness due to gap opening along the joints and to non-linear behavior of the concrete in compression. At the third and fourth point, post-tensioning steel yielding and confined concrete crushing occurs respectively. The steel is already in a plastic state and the pre-cast concrete is failing due to crushing. Up to yielding of the post-tensioned steel there is very little damage in the concrete panels because of the spiral reinforcement providing confinement. At the fourth stage or the failure stage the confined concrete undergoes crushing due to fracture of the spiral reinforcement.

Figure 2. Base Shear vs Lateral Drift



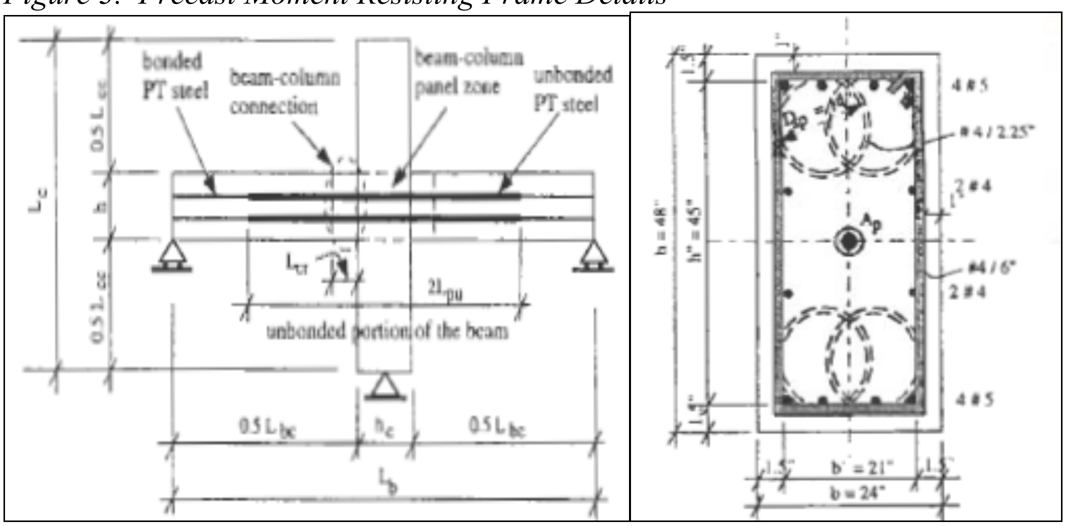
The behavior of this type of system is governed by the performance of the horizontal joints. These joints can either open a gap as in flexure or slip in shear. Gap opening behavior is normal and expected and is restored by the post-tensioning force and gravity loads. For shear slip behavior there is no restoring force available to center the structure. Slip shear is a very important problem that needs to be accounted for in the design. Research has shown that an unbonded post-tensioned precast wall has larger displacements under seismic loading when compared to the traditional reinforced concrete wall, but the reinforced concrete wall will experience larger residual displacements at the end of loading.

- ***Unbonded Post-Tensioned Precast Moment-Resisting Frames***
  In this type of system precast beams are post-tensioned using bars or strands to precast columns without any bond between the tendon and the concrete in the joint region. Details of this connection can be observed in Figure 3. During loading the beam-column joint will open due to flexure and it will reclose during unloading due to the strands remaining elastic. This process will occur at every joint throughout the structure providing a mechanism for the frame to self center. Shear force is

carried by friction in the interface between the column and the beam provided that they are compressed together trough the elastic post-tensioning strands. This ductile connection behaves in a non-linear elastic fashion while the rest of the beam and column remains elastic. The bars or strands must remain unbonded because this delays the development of inelastic deformation in the post-tensioned steel and will therefore maintain the restoring force through large deformations. To further delay inelastic deformation of the PT steel, the PT steel is placed close to the centroid of the beam cross section (El-Sheikh, Pessiki, Sause, Lu 2000).

Through past research it has been found that larger values of rotation at the connection can be achieved by ensuring the following: an increase in unbonded length, a decrease in post-tension strand eccentricity, an increase in volumetric ratio of spiral reinforcement, and a decrease in initial stress in concrete and post-tensioned steel. It was also found that choosing a beam section with a width greater than two times the depth of the compression stress block will help to avoid failure in the confined concrete in the transverse direction.

Figure 3. Precast Moment Resisting Frame Details



- ***Steel Moment Resisting Frames with Post-Tensioned Connections***
  This system is very similar to the one just discussed except that steel beams and columns are post-tensioned to each other instead of precast concrete. The strands run parallel to the beam and enter the column flanges where they are anchored. These strands which are compressing the edges of the beam against the columns flange create a moment resisting mechanism while angles bolted from the beams to the columns flanges or shear tabs will resist shear forces.

  These bolted angles serve not only to resist shear but as energy dissipation devices which will yield under loading. It has been shown through previous research that three plastic hinges form in these connection angles. Two of these plastic hinges will form in the fillet of each angle, another one near the bolts where they connect to the columns. Figure 4 shows a detailed description of this connection. Reinforcing plates are welded to the beams flanges which control beam flange yielding and local buckling. Shim plates should also be placed between the column flange and beam flanges so that only the beam flanges and reinforcing plates are in contact with the column.

Figure 4. Steel Moment Frame with Post-Tensioned Connection

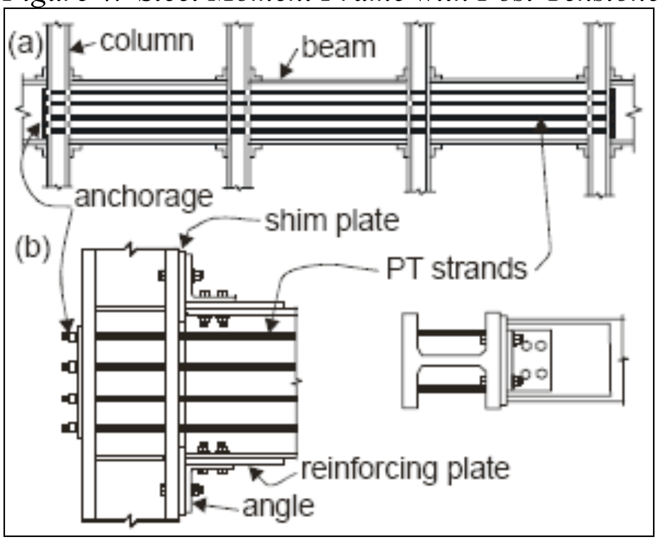
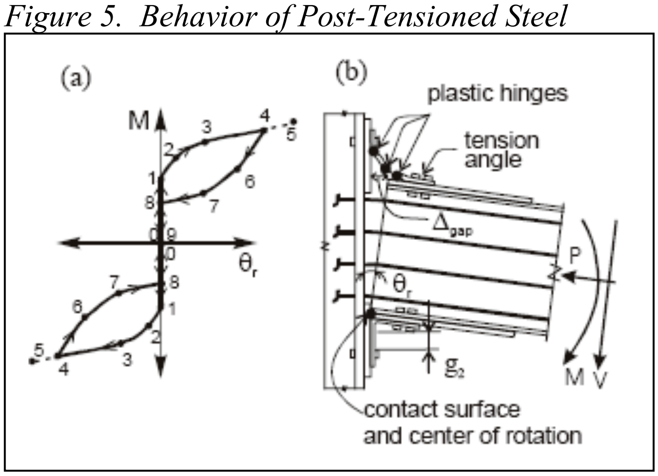


Figure 5 shows the moment-rotation hysterisis loop for a post-tensioned steel connection and a design example. In Figure 5.a it can be observed that between stage 0 and 1 the connection will have an initial stiffness (before the gap opens) equal to that of welded connection. At point 2 the seat angle will yield. The angle will become plastic through stage 3. The moment reaches a maximum at stage 4 where unloading begins. If loading were to continue the strands would yield at stage 5 which would cause major problems. During unloading the angle would dissipate energy while the gap closes due to the restoring forces of the tendons where the connection finally reaches step 8 with no plastic hinge in the beam or the column.

Figure 5. Behavior of Post-Tensioned Steel



Previous research has proved that this system has a very efficient behavior as long as the beams do not buckle or the strands undergo yielding. Beam buckling prevents the frame from self-centering and limits the ductility (M. Garlock, J. Ricles, R. Sause 2005). If the above cases are not reached through the specification of limit states the beams and columns remain elastic while the plastic hinges form in the angle seats. These limit states are very important to ensure proper behavior and can be enhanced by using longer reinforcing plates or a smaller initial post-tensioning force. To prevent strand yielding, a larger number of strands, with a smaller initial post tensioning forcer per strand, is recommended (M. Garlock, J. Ricles, R. Sause 2005).

Through this research it was found that increasing the number of strands provides larger connection moment and increases ductility. By increasing the number of strands the stiffness is being increased which increases connection moment. Another advantage of having many strands is that the initial post tensioning force in each strand will be smaller which makes them less vulnerable to yielding. It was also found that specimens with a smaller total initial stiffness open the gap earlier and have a larger relative rotation in the connection which sometimes leads to fracture of the seat angle. The seat angle should not fracture since it is an essential energy dissipater. The following are some predictive equations that were found to match the experimental data with great accuracy. The equations are based on the free body diagram shown in Figure 6.

The summation of moments about the beams centroid gives:

$$M = (d_1 - d_2)V_a + Cd_2 + M_a^T + M_a^C$$

where $C = T + F_{fd} + V_a$, and by substituting C:

$$M = d_1 V_a + (T + F_{fd})d_2 + M_a^T + M_a^C$$

where F_{fd} is an additional axial force in the beam produced by the interaction of the post-tensioned frame with the floor diaphragm, V_a is tension angle shear force, M_a^C and M_a^T are moments in the compression and tension angle at the plastic hinges respectively, and T is the strand forces. Garlock et al. (2003) came up with an empirical equation for the shear in the angles V_a:

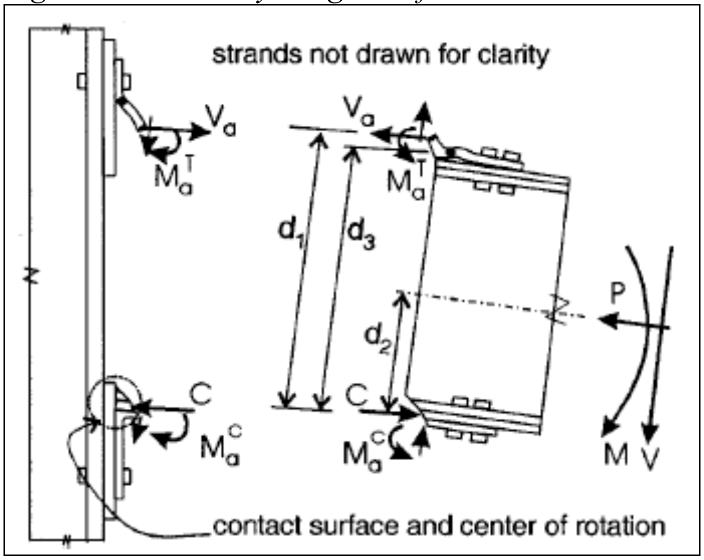
$$V_a = \underbrace{(1.13 + 0.047\Delta_{gap})}_{\beta} \cdot \underbrace{(1.35 - 0.027t)}_{C_V} \cdot \frac{2M_{a,p}}{g_2}$$

Where delta gap is the amount of gap opening in mm, $M_{a,p}$ is the plastic moment capacity of the angle cross section, and g_2 id the distance between the centerline of the fillet on the angle leg and the inside edge of the column bolt nut. The total post-tensioning force in the strands is given by:

$$T_{th} = T_0 + 2d_2\left(\frac{k_s k_b}{k_b + k_s}\right)\theta_r$$

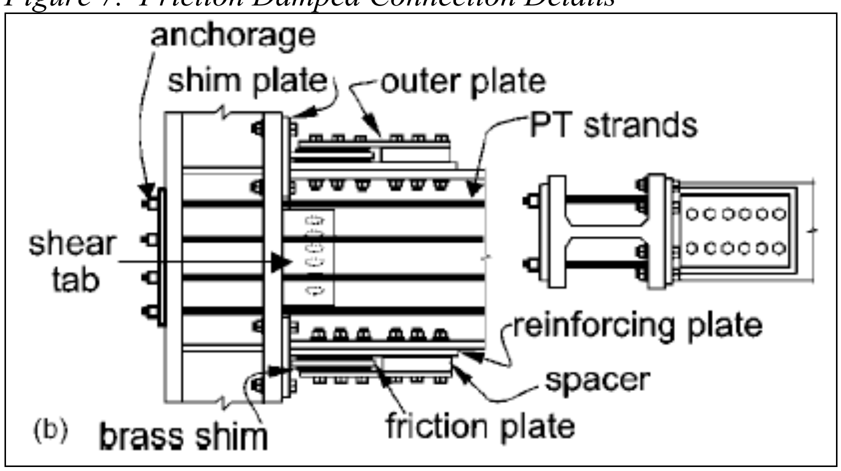
Where k_s and k_b are the axial stiffness (AE/L) of the strands and beams respectively, L is the length of one bay, and the factor of 2 is to take into account two connections per bay.

Figure 6. Free Body Diagram of Steel Post-Tensioned Connection



An alternative to relying on the seat angles to dissipate energy is to implement a friction damped connection. These devices consist of a friction plate sandwiched by two brass shim plates that are inserted between the beam flange reinforcing and outer plates (Rojas, Ricles, Sause 2005). When loading is applied the beam flanges and outer plate slide against the friction plate as the beam rotates. Long slotted holes must be opened in the friction plates so the beam can move. Gravity loads are carried by a shear tab which must be bolted to the beams web with slotted holes to allow for translation. The amount of friction force needed at the connection can be determined from the required flexural capacity. Figure 7 shows the details for this friction damped connection.

Figure 7. Friction Damped Connection Details



- **Unbonded Post-Tensioned Bridge Piers**
  Although very little information was found on this topic these systems behave and are assembled in a similar fashion to the precast wall system. Figure 8 shows how the pier would be post-tensioned. Figure 9 is from some research done in Berkeley were a post-tensioned bridge pier finished the loading cycles with very little residual drifts when compared to its traditional counterpart.

Figure 8. P-T Bridge Pier

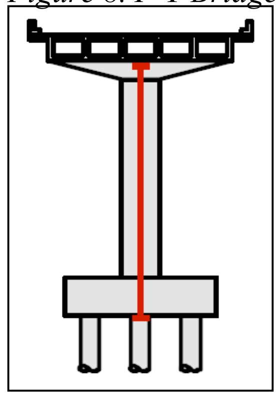
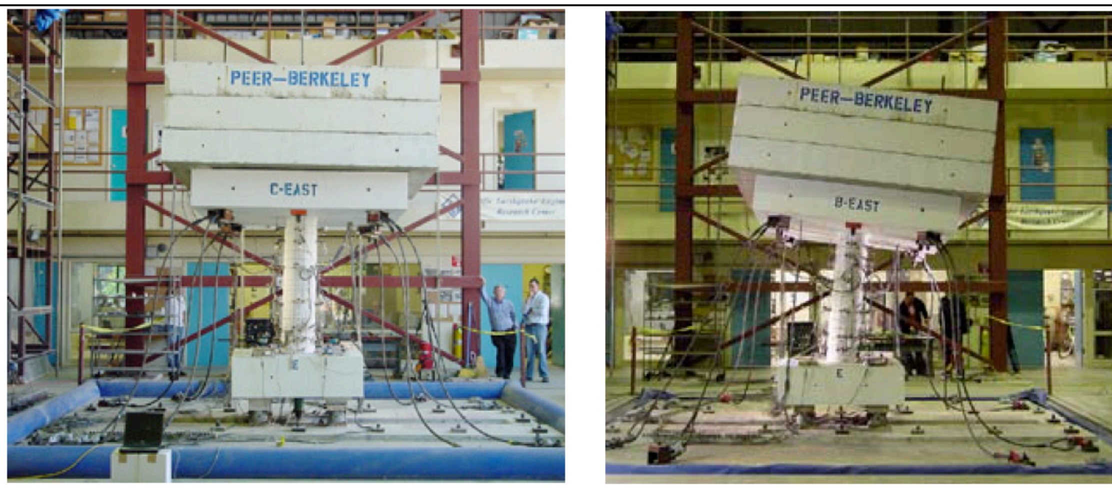


Figure 9. Bridge Pier Test done at Berkeley



Self-centering with UBPT
After maximum level run

Conventional RC
After maximum level run

CONCLUSION

Self-centering systems are still in early research stages but may prove to be very efficient and useful in the near future for seismically active areas. The idea of having a structure that can "self-center" itself and therefore have zero residual displacements at the end of an earthquake can be very powerful not only in an economic sense but in a safety sense. This paper discusses four major applications of this technology: unbonded post-tensioned precast concrete walls, unbonded moment-resisting frames, steel moment resisting frames with post-tensioned connections, and unbonded post-tensioned bridge piers.

The unbonded post-tensioned precast concrete walls has proven to be very efficient in controlling residual drifts, although it will experience larger rotations during loading when compared to traditional RC systems. One of the major design problems with this system is that it may experience residual shear drifts from wall to wall. It is important that designers provide enough friction force between each wall as to avoid this problem. The second system that was studied, unbonded post-tensioned precast moment-resisting frames, is composed of precast beams and columns with strands running through them. The strands or bars must be unbonded to ensure proper behavior, and enough compression must be applied for the beam-column interface to carry the necessary shear forces through friction. The steel moment resisting frames with post-tensioned connections has the most research behind it. These connections rely on the force of the post-tensioned bars or strands to maintain equilibrium. One important detail about this connection are the energy dissipation devices. They consist of either seat angles that yield under loading or friction devices that dissipate energy. Although much more research is need for the seismic design community to adopt this system they have already proven to be very advantageous.

Some of these advantages include the following: 1) Structural member size and complexity similar to conventional seismic resistant system, 2) Initial lateral stiffness same as conventional structures, 3) Reduced damage since SC systems are designed to resist design EQ without members being damaged, 4) Controlled lateral force versus lateral drift behavior under EQ loading, 5) Lateral force versus lateral drift behavior that softens without significant inelastic deformations of the main structural members therefore without the resulting structural damage and residual drift since the softening behavior is created by the opening if gaps, 6) Ductility capacity very large and not totally controlled by material ductility, 7) Energy dissipation elements designed for that purpose so energy not dissipated by damage to structural elements, 8) Angles easily replaced, and 9) Welding is not necessary.

With all the advantages listed above and the current research being performed, self-centering systems may be the future of seismic design. They address the ultimate problem of structures which is to find a way to dissipate energy and remain elastic. These systems have found a way to do this and more without affecting critical structural components when subjected to seismic loading.