Review of Self-Centering Connections, as a NewSeismic Resistance Methodology

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Abstract:

Conventional structure designed in a way that energy dissipation in structure happens through inelastic deformation of structural members. The drawback of this kind of design is permanent deformation in structure which leads in structural permanent deformation. Permanent structural deformation will cause expensive repair process if possible or may lead to collapse of the system under seismic force.

Self-centering connection is a new seismic-resistance system which has been studied experimentally and numerically during past recent years. Self-centering connections take advantage of gap opening strategy between structural member accompanied by a kind of energy dissipation device to provide energy dissipation property without inelastic deformation in main structural members. Self-centering connection contains post tensioning elements at the connection to take the structure back to its plumb condition.

This paper provides a review on the research papers discussing different types of self-centering seismic-resistance system. Self-centering connections categorized in self-centering connection with post-tensioned elements and self-centering connections with energy dissipation devices and post-tensioned elements.

Keywords - *review, Self-centering, Post-tensioned, Seismic, energy dissipation*

I. INTRODUCTION

Self-Centering (SC) systems have been investigated by several researchers utilizing both analytical and experimental methodologies inthe previous decade[1], [2], [3]. SC connections are typically embedded in different structural systems such as moment resisting frames [4] and braced frames [5] as well as different parts of a steel structure [5], reinforced concrete (RC) [6], and wooden frames [2] with the aim of reducing deformation of the main structural members. The SC connection takes advantage of Post-tensioned elements (PT) to restore the structure back to the plumb situation and energy dissipation devices to serve as an energy dissipation device to dissipate the related energy.

Conventional structures designed based on available structural codes should have the capabilities for ductile inelastic response and lateral force energy dissipation. Energy is dissipated through hysteretic yielding of the main structural elements. This energy dissipation is directly associated with structural damage to the structure and can lead to potentially large, permanent inelastic deformations. These permanent deformations lead to significant repair or replacement cost and associated expenses to regain normal operation, if possible. Under sever plastic deformation the repair cost maybe more than new structure construction cost. The advantage of SC connection in comparison withconventional structure is that the energy dissipation would be through special devices rather than hysteretic energy dissipation by main structural members. Damage reduction, or lateral displacement control, reduce the member's inelastic deformations and energy dissipation under lateral force which is produced by energy dissipation (ED) devices and not due to plastic deformation in members are advantages of SC connections [7], [8].

II. SELF-CENTERING CONNECTIONS WITH POST-TENSIONED ELEMENTS:

The post-tensioned connection introduced by Ricles et al [9]. is a beam-to-column connection constructed by high-strength PT strands. The PT strands run parallel to the beam and through the column and are anchored outside the connection [9]. Angles would dissipate the energy through yielding [9]. Some of the advantages of a PT connection include elimination of a need for field welding, similar stiffness as a welded connection, self-centering behavior without residual deformation and limiting the damage to the angels of the connection [9]. Gap opening and closing characterized the flexural behavior of a connection under cyclic loading (as shown in 1-b). The moment at gap opening is called the decompression moment. Decompression is event 1 in Fig.1. With continued loading, the angles will yield (event 2). Full plastic yielding of the angles is event 3. With continued loading, the posttensioning strands will eventually yield at event 5. The Moment-Rotationrelationship is essentially linear between events 3 and 5. If unloading occurs at event 4, the angles will dissipate energy (between events 4 and 8 in Fig. 1.) until the gap between the beam flange and the column face is closed at event 8. A reversal in yielding of the angles (starting at event6) is needed to close the gap. A complete reversal in moment will result in similar connection behavior in the opposite direction of loading, as shown in Fig. 1. [9].

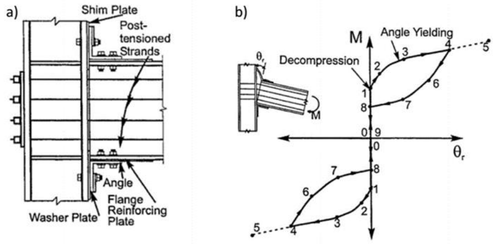

Fig. 1: a) Posttensioned (PT) Steel Connection b) Moment-Rotation Behavior of PT Connection (after Ricles et al) [9]

Although the system proposed by Ricles et al has a self-centering advantage but dissipating energy through angles can be considered as a drawback for this system as the access to deformed angles for their replacement would be hard.

Chou et al [10] introduced a post-tensioned self-centering moment frame as an alternative to the steel special moment frame. An alternative method for evaluating bending stiffness of columns and compression forces in the beams based on a deformedcolumn shape was presented that matches the gap-opening at each beam-to-column interface [11]. Analytical method for evaluating the effects of column restraint resulting from gap openings at beam to column interfaces in a post-tensioned self-centering moment frame was evaluated through full scale experimental testing. The analytical formulation is supported by a cyclic analytical analysis as well as cyclic test of a full-scale, two-bay by first-story PT frame.

A column with a post-tensioned base connection was studied experimentally and analytically by Chi and Liu [12]. The connection shown in Fig. 2. eliminates structural damage at the column base. This connection provides softening behavior by allowing a gap to open at the base of the column and elongation of PT bars instead of yielding in columns. Buckling of restrained steel (BRS) plates provides additional energy dissipation for system [12].

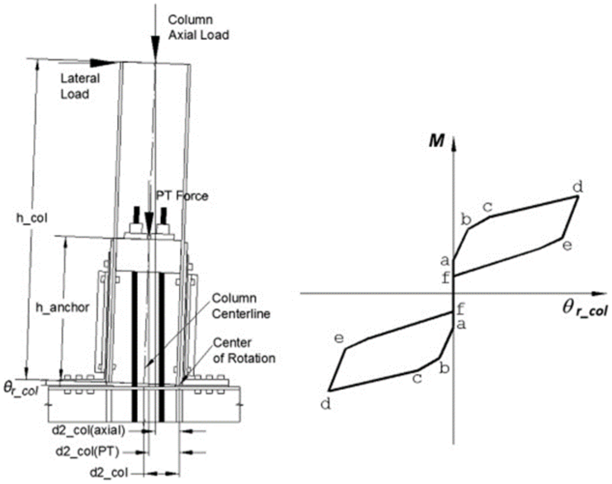

Fig.1: Idealized Behavior of PT Column Base Connection (Hoseok Chi 2012) [12]

A typical moment-rotation for a PT column base connection is shown in Fig.2. The response is characterized by gap opening and closing at column-beam interface. As the gap opening increases due to the applied moment, the PT bars and BRS plates begin to deform. The PT bars elongate, whereas one of the BRS plates elongates and the other plate shortens. After decompression occurs (event (a) in Fig. 2.), additional axial force from the PT bars as well as BRS plates is developed in the PT column base connection, providing additional moment resistance [12]. As the gap opening increases further, the BRS plates begin to yield at event (b). The stiffness of the PT column base connection after decompression is associated with the axial stiffness of the PT bars and initial stiffness of the BRS plates [12]. As the gap opening increases, the BRS plates reach their tensile strength (event (c)). The connection stiffness between event (b) and event (c) is associated is associated with the axial stiffness of the PT bars and post-yield stiffness of the BRS plates. After the BRS plates reached the full capacity (event (c)–event (d). When unloaded (event (d)–event (e)), the BRS plates dissipate energy. Point (e) corresponds to the typical unloading point on a yielding element [12].

The PT column base connection proposed by Hoseok et al [12] eliminate damage to columns member in a SC steel moment resisting frame while PT high strength bars provide restoring forces and BRS plates dissipate energy. PT column base connections were able to withstand 4% story drift without structural damage in columns and the BRS plates as the main source of energy dissipation were able to withstand 5% drift without failure [12].

Studying the connections with Post-tensioning elements [13], [14] show that although self-centering would be provided by PT elements but energy dissipation happens through plastic deformation in some structural elements at connection that can be considered as a disadvantage for Post-Tensioned connection therefore it is desired that PT elements used along with kind of replaceable energy dissipation devices.

III. SELF-CENTERING CONNECTIONS WITH PT AND ENERGY DISSIPATION ELEMENTS

Energy dissipation devices are used in structures along with PT elements in order to provide energy dissipation without significant inelastic deformation, restoring elastic forces through PT elements and returning the structure to its initial position thereby eliminating large displacements.

Post-tensioned energy dissipation connection for the moment-resisting steel frame is studied analytically and experimentally by Christopoulos et al [15]. The system proposed consists of high strength posttensioned steel bars along with energy dissipating bars that used at connections to provide a ductile connection as well as self-centering capabilities for the system [15].

This connection dissipates energy through energy-dissipation bars and self-center through post-tensioning bars. Energy-dissipation bars attached to the beams and columns of the frame by welded coupler. When beam rotates, the energy-dissipation bars deform inelastically in tension or compression to dissipate energy. Post-tensioned bars run through the beam and connected to columns in order to self-center the structure Fig. 3-b.

Under cyclic loading the moment-rotation hysteretic response developed at the beam-to-column interface by the combination of PT and ED bars as shown in Fig.3-b. This combination of moment-rotation relations results in a flag shaped hysteresis in which energy is dissipated while the system retains its self-centering capabilities [15].

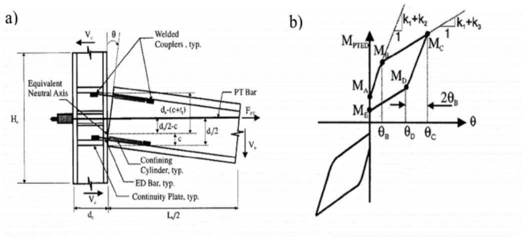

Fig.3 a) Free Body Diagram of Steel Frame with Posttension Energy Dissipating Connection, b) Moment-Rotation of Posttension Energy Dissipating Connection After (Constantin Christopoulos 2002)

Analytical study was done to develop the moment-rotation relationship of the connection by Christopoulos et al [15]. Developed model accurately predict the connection behavior and provide the procedures for designing post-tensioning and energy-dissipating bars for the connection [15]. Energy-dissipation bars were tested in order to assess the tension-compression cycles of the bars that it was found that the energy-dissipating bars were able to yield by axial loads to dissipate the energy [15]. A cyclic test was also performed on a beam to column connection that shows the post-tensioned bars were able to self-center the structure and large deformations were achieved without damaging the rest of the frame [15].

Iyama et al [16] developed a friction device as an energy dissipation device for Self-Centering Post-Tensioned steel beam-to-column connection. Friction device is named bottom flange friction device (BFFD) and is located beneath the beam [16]. As it can be seen in Fig 4-a the BFFD consists of a vertically oriented friction plate with slotted holes that is welded to the bottom beam flange, and two outer built-up angles that are bolted to the column face [16].

The conceptual relationships between the moment in the beam at the column face (M) and relative rotation between the beam and column (θr) of the BFFD connection is shown in Fig. 4-b. Under applied loading, the connection has an initial stiffness similar to a fully restrained welded moment connection, where θr equals zero (event 0 to 1). Once the applied moment overcomes the post-tensioning force, decompression of the beam flange from the column face shim plate occurs, although gap opening is not observed initially because the friction devices have not begun to slip. As the applied moment continues to increase, the connection rotation is resisted by friction. Rotation and gap opening are imminent (at event 1) once the applied moment is equal to the sum of the moment capacities due to post-tensioning and friction. This event is referred to as imminent gap opening (IGO).

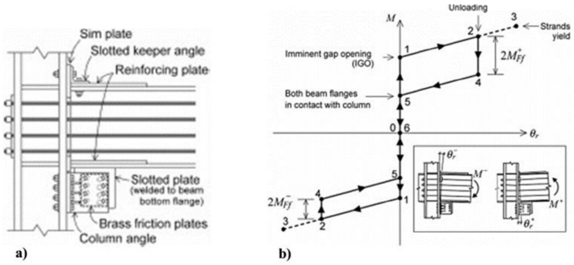

Fig.4: a) BFFD Connection, b) Idealized Moment-Rotation of BFFD Connection After (J.Iyama 2009)[16]

After IGO, the moment capacity of the connection increases because elongation of PT strands produces additional axial force. Upon unloading at event 2, θrremains constant. Between events 2 and 4, moment contribution from the friction device changes direction due to a reversal of the friction force, where at event 4reversal of the friction force is complete. Between events 4 and 5, θrreduces to zero as the beam flange comes back in contact with the column flange shim plate but is not compressed. Between event 5 and 6, the moment decreases to zero as the beam flange compresses fully against the column face shim plate [16].

Static push-Over and Time-history analyses were done on BFFD by Iyama et al. Response from numerical analysis are in agreement with the design curves. BFFD would be a great choice for the friction device that is going to be considered for steel truss self-centering structure but the asymmetric response is a draw back and should be fixed.

Finite element analysis and cyclic tests were conducted on self-centering moment connections with beam bottom flange energy dissipation by Chou and Lai [10]. The frame chosen contains concrete columns and steel beams, beams are embedded into the concrete column and are post-tensioned by high-strength steel strands, energy dissipaters are connected to the beam bottom flange by bolts Fig. 5.

Fig. 5–b shows the moment provided by strands and energy dissipater. The hysteretic loop is un-symmetrical because no energy dissipater is located on the beam top flange and beam decompression in the negative bending (point 1') occurs earlier than that in the positive bending (point 1).

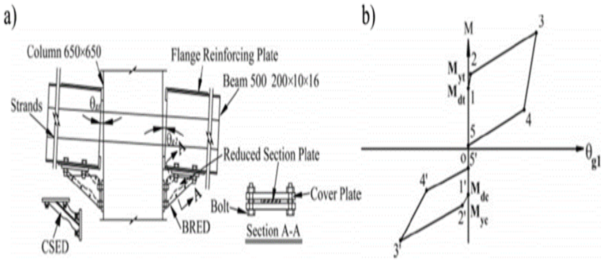

Fig.5: a) Post-Tensioned Frame with Bottom Flange Energy Dissipation, b) Moment-Rotation of a Connection (Y.-J. L. Chung-Che Chou 2009) [10]

When the beam is in positive bending, the energy dissipater is under tension. Once the decompression moment is exceeded at point 1 the energy dissipater yields at point 2. When the load is reversed at point 3, the energy dissipater yields after point 4 is reached and the gap closes at point 5, generating a self-centering response. Similar responses occur with small energy dissipation when the beam is in negative bending [10].

Experimental analysis and cyclic tests are conducted on three post-tensioned connections to investigate the cyclic performance of energy dissipaters. Cyclic test results show that (1) energy dissipation, moment, and flexural stiffness of the beam in positive bending are larger than those of the beam in negative bending, (2) the location of the compression toe at the end of the beam stabilizes at the junction between the beam flange and web after an inter story drift of 1.5%, in which the gap opening angles of the beams are similar in both bending directions [10].

Friction-damped, post-tensioned SC connections for moment-resisting frames were proposed by Kim and Christopoulos [17]. The connection eliminates the weld at the beam-to-column interface and provides energy dissipation. A bolt-stressed frictional devices consisting of stainless-steel interfaces and new non-asbestos organic break lining pads provide energy dissipation. Post-tensioned strands run parallel to the beam that provides SC capacity. Friction devices are installed symmetrically (Fig. 6-a) on the top and bottom flange to simultaneously provide self-centering capacity and energy dissipation [17].

The system proposed by Kim consists of PT and Friction devices. The PT elements (bars) are anchored outside of the flange faces of the exterior columns and run through the interior column flanges and provide the initial force in the connection. The frictional energy dissipating devices are located on the top and bottom beam flanges. As moment is applied to the connection, the initial PT force is overcome and a gap opens at the beam-to column interface (Fig. 6-b). The PT bars elongate with the widening of the gap and axial shortening of the beam. The opening force is countered by the frictional energy dissipating devices at the top and bottom of the connection. Along with the friction force, the PT bars provide the restoring force and SC capabilities.

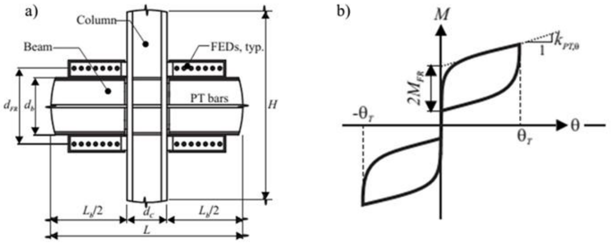

Fig. 6. a) SC connection, b) Moment-Gap Opening Angle Relation [17]

The connection was experimentally tested for both the exterior and interior beam-column loading within the self-centering range. The interior column assembly was also tested beyond the self-centering range to study the behavior. They were examined under cyclic loading for their structural behavior. The connection exhibited good energy dissipation without beam or column inelastic deformations and without residual story drift. At the ultimate stage, the connection can provide a ductile response with the formation of flexural hinges in the beam sections.

Self-centering rocking-core system developed by Belbo and Roke to limit damage and residual drift. The SC rocking system (Fig. 7) consists of beams, columns, and braces branching off a central column. A central column is in the middle of the bracing bay and all other members such as beams, columns and braces are branching off it. Vertically oriented post-tensioning bars provide additional overturning moment resistance and help to reduce residual drift. Vertical PT bars that provide self-centering behavior and additional stiffness are located at the ends of the beams. The SC rocking system is isolated by lateral bearing at the end the beams to permit vertical movements also the friction generated at these bearings is used to dissipate energy to reduce the seismic response [18].

Nonlinear static and dynamic analysis performed on suggested SC Rocking system shows that this system is an effective lateral-force system that allows more ductility in comparison with conventional CBF systems.

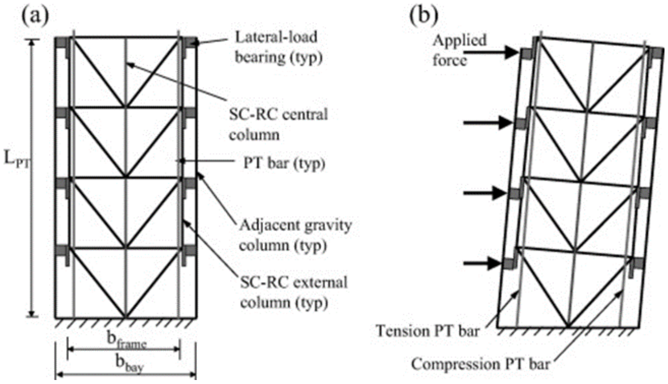

Fig.7: SC Rocking System Concept: Configuration, Rotation about the base of the SC_RC Central Column (After Belbo and Roke2015)[18]

IV. CONCLUSION

Self-centering connection as a new system to resist seismic forces has been reviewed. SC connections have the capability to mitigate the damage to structural member under designed earthquake forces. Summary of the research which have been done on SC connection show that:

1. SC connection are economical as the structural member size are similar to conventional structures
2. SC connection mitigate the damage to the structure
3. SC connection eliminates damage of structural main members and connections
4. Energy dissipation in SC connection is through energy dissipation elements not as a result of damage to main structural members.
5. Initial stiffness of SC connection is the same as stiffness of conventional structure.

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