June 01, 2013

A synopsis of sustainable structural systems with rocking, self-centering, and articulated energy-dissipating fuses

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Report No. NEU-CEE-2013-01

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This research was funded by a grant from Nippon Steel & Sumiken Engineering Co. and by Northeastern University. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors

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Boston, Massachusetts

June 2013

ABSTRACT

This synopsis examines previous research related to seismic energy-dissipating structural systems of buildings. These systems are grouped into self-centering systems, systems exhibiting rocking behavior and systems with energy-dissipating fuse elements. Bracing systems, precast buildings, steel frames with post-tensioning strands, rocking shear walls and some similar structural systems are investigated for self-centering behavior. Rocking motion reduces seismic loading and ductility demands by generally forcing structural behavior to remain in the elastic range. Energy-dissipating fuses are structural elements that protect the surrounding structure by absorbing energy from an earthquake that would otherwise be absorbed by the primary girders, columns, and braces of the structure, as well as nonstructural elements.

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SUSTAINABLE STRUCTURAL SYSTEMS WITH ARTICULATED ENERGY-DISSIPATING FUSES

1. Introduction

This literature review examines previous studies related to energy-dissipating systems. It begins with a general discussion of various structural systems that absorb energy during seismic events. These systems are grouped into self-centering systems, systems exhibiting rocking behavior, and energy-dissipating systems. The report then examines specific case studies of each type of system. For example, precast concrete walls, braced frame systems with fuse, moment resisting frame systems with fuses, systems with friction dampers, and specific instances of designs for high-rise buildings are examined under the category of structures with fuses. Post-tensioning (PT) tendons in concrete frames, damage controlled self-centering structures, damage-free seismic resistant SC-CBFs, self-centering column bases, and self-centering MRFs are examined under the category of self-centering systems. Following the summary of self-centering systems, structures with combined rocking and fuses are outlined, such as braced frame fuse systems, core suspended isolation systems, rocking frames with yielding base plates due to uplift, concrete walls with energy-dissipating devices, and supplemental damping systems. Structures with self-centering and fuses are then examined, including examples of PT-SCED braced frames, wedge devices, precast moment-resisting frames with PT strands in the connections, unbonded PT hybrid coupled wall subassemblages, and RC frames upgraded with SMA self-centering energy-dissipating braces. This report concludes with structures that combine all of the above energy-dissipating systems: fuses, rocking and self-centering. This includes structures with walls pre-stressed with partially unbonded tendons, hybrid systems for frames and shear walls, self-centering earthquake-resisting systems, SCPT beam-column connections in steel frames, self-centering steel frames with rocking beams and base plates, rocking frames with metallic structural fuses, and structures with SC-SPSW and PT connections. The report introduction outlining these systems is then followed by a summary of each of the many significant references available on these topics. Towards the end of the report, tables are provided that provide the highlights of the research reported in each of these references. A supplemental bibliography of additional related references and a table of abbreviations and symbols are included at the end of the report.

1.1. Structures with Energy-Dissipating Fuses

Braced fuse systems and joint fuse systems are examples of structures with energy-dissipating fuses. Kassis and Tremblay (2008) examined braced fuse systems for low-rise steel buildings. In this study, a braced fuse system was used to keep the braces in tension during ground motion, allowing for an increase in the design forces. The configuration of the braced fuse system is shown in Figure 1.

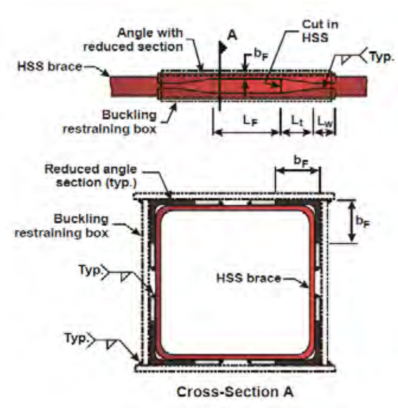


Figure 1 Braced Fuse System [after Kassis et al. 2008]

The results of quasi-static cyclic tests verified the seismic performance of the system and the effects of braced fuse systems on force demand in low-rise steel buildings. From test results, it was concluded that adding braced fuses in tension/compression (T/C) to moderately ductile (MD) braced frames was an effective way to reduce the connection tension design loads. However, one negative of this system is that the braced tension fuse systems are not replaceable if the connections are welded.

DSDF and SHJ have also been used as energy-dissipating fuses in the structures. As shown in Figure 2, the fuses were examined by MacRae (2008). The SHJ is a replaceable element that allows significant rotations of the beam end relative to the column face. The DSDF system showed no significant damage and behaved in an isotropic manner. Moreover, it exhibited self-centering capabilities. The floating plate can be replaced after yielding, since it is bolted to the system.

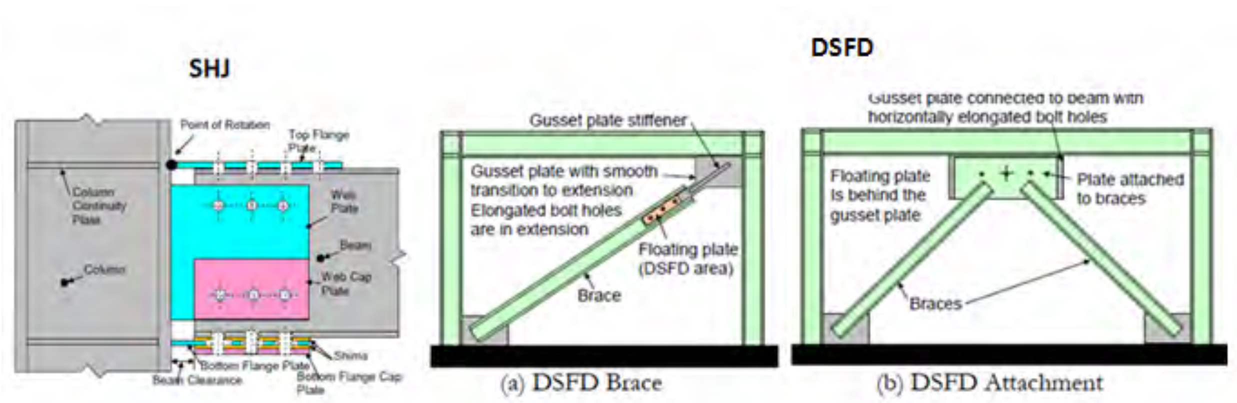


Figure 2 SHJ and DSFD [after MacRae et al. 2008]

1.2. Structures with Self-Centering Systems

PT tendon applications in concrete frames were examined by Walsh and Kurama (2008). The inclusion of unbonded tendons in structures reduced concrete cracking and delayed strand yielding. Moreover, this structure offers self-centering capability through PT force. Figure 3 shows unbonded PT strands used in frames, shear walls and coupled walls.

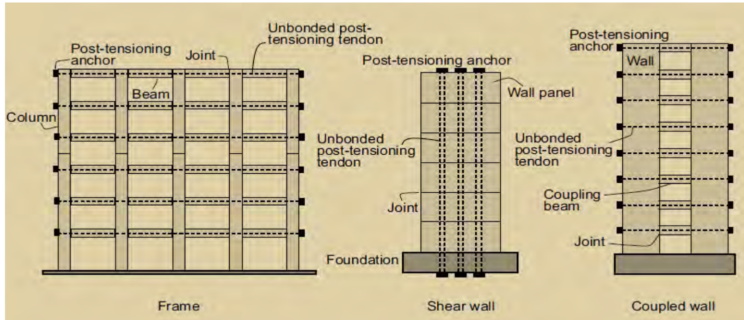


Figure 3 Applications of Unbounded Post Tensioning Tendons [after Walsh et al. 2008]

Roke et al. (2009) examined damage-free SC-CBFs. This frame configuration aimed to minimize structural damage under seismic loading. Column base connections permitted the columns to uplift at the foundation, as shown in Figure 4. Gravity loads and PT steel resisted column uplift and provided a restoring force to the structure after uplift.

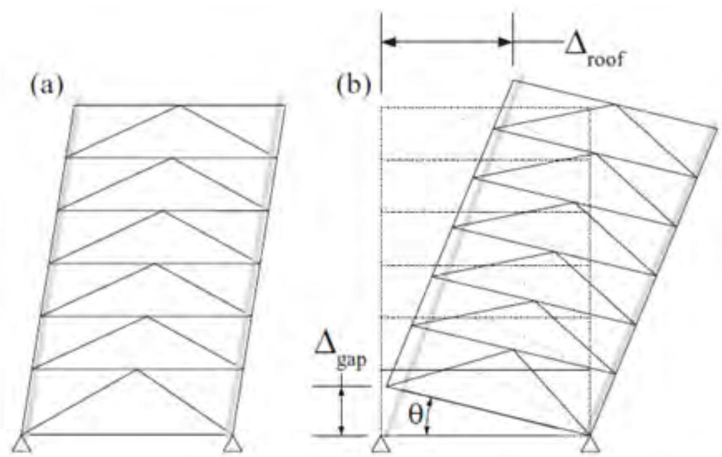


Figure 4 Damage-Free Seismic-Resistant SC-CBF [after Roke et al. 2009]

1.3. Structures with Rocking and Energy-Dissipating Fuses

A core suspended isolation system (CSI) was examined by Nakamura et al. (2008). This pendulum isolation system consists of a reinforced concrete core on top of which sits a seismic isolation mechanism composed of a double layer of inclined rubber bearings. As shown in Figure 5, the seismic isolation mechanism allows swaying and swinging motion of the hanging structure, as well as rocking motion of the core. Nakamura examined the hysteretic characteristics of full scale rubber bearings under rotational and horizontal displacements.

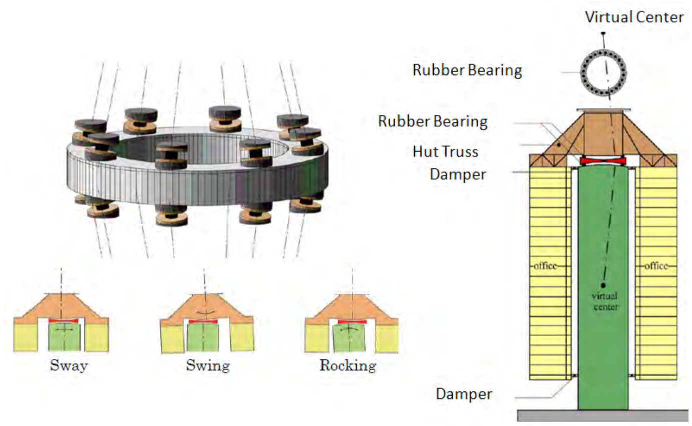


Figure 5 Core Suspended Isolation System [after Nakamura et al. 2008]

1.4. Structures with Self-Centering and Energy-Dissipating Fuses

Clifton et al. (2003) examined two new semi-rigid joints for moment resisting steel frames, as shown in Figure 6. Both the FBJs (Flange Bolted Joints) and SHJs (Sliding Hinge Joints) have been developed to undergo rotation during severe earthquakes, while suffering minimal structural damage. FBJs and SHJs are intended for low and high levels of design ductility demand, respectively.

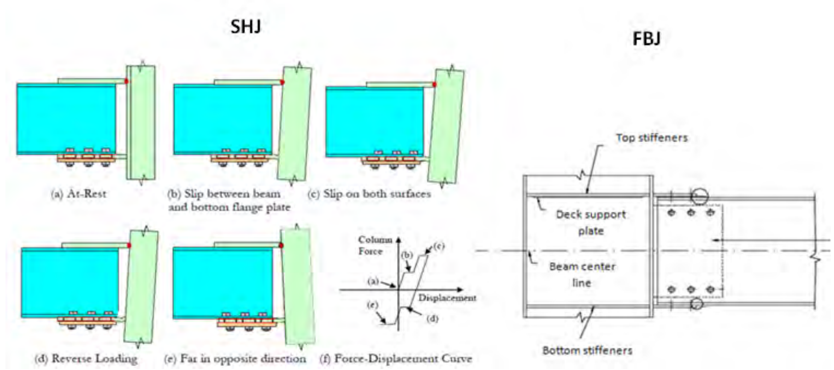


Figure 6SHJ and FBJ Types of Joints [after Clifton et al. 2003]

The joints were designed and detailed to withstand the expected inelastic rotation associated with the design level ultimate limit state earthquake with negligible damage. However, the joints are also able to withstand a greater level of inelastic rotation, associated with more severe events.

Christopoulos et al (2008) examined buckling restrained and self-centering bracing systems. The purpose of this system was to eliminate damage to structural elements and minimize residual deformations by means of a brace member which can undergo large axial deformations. The experiment resulted in similar peak inter-story drifts in self-centering energy-dissipating frames (SCED) and buckling restrained braced (BRB) frames with less damage concentration and smaller residual lateral deformation in SCED system.

Braced fuse systems consist of an energy-dissipating mechanism (SCED bracing), structural steel member, pre-tensioned tendons, and a fuse element that can be replaced after yielding if it is bolted, as seen in Figure 7.

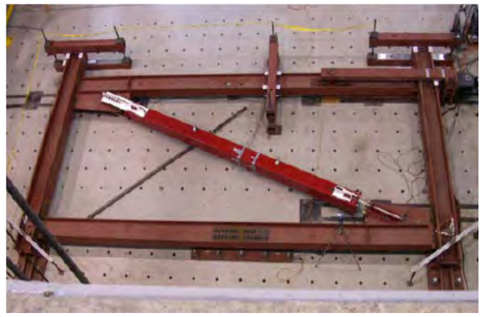


Figure 7 Self-Centering Braced Frame [after Christopoulos et al. 2008]

In this study, nonlinear dynamic analyses of building structures from 2 to 12 stories were performed to evaluate the performance of SCED braced frames with friction energy dissipation. Cyclic quasi-static and dynamic tests with simple shear beam to column connections show similar peak inter-story drifts in SCED and BRB braced frames, but less damage concentration and smaller residual lateral deformation occurred in the SCED system.

1.5. Structures with Rocking, Self-Centering and Energy-Dissipating Fuses

Azuhata et al. (2008) investigated self-centering systems composed of rocking structural members, in which part of the system was allowed to uplift during an earthquake. This system can prevent steel building structures from yielding and suffering from excessive residual drift after severe earthquakes by using the effect of building's self-weight to self-center the structure. Force deformation relationships of the rocking structural members, the self-centering ability of the system and the energy dissipation mechanism were investigated by means of numerical models.

Simple rocking systems allowed the structure to uplift and can be applied to slender building structures. Rocking systems with footing dampers controlled the uplift response, and coupled rocking systems connected two rocking systems and improved energy-dissipating performance when compared to other methods.

Azuhata et al. (2008) investigated a steel frame system with a rocking mechanism composed of rocking structural members, coupled braced units with yielding base plates and one-side rocking beams. Dampers were used as connection devices between two narrow braced frames and were allowed to deform only vertically, as shown in Figure 8. Each braced unit was connected to the base of the structure by thin base plates. The structure could rock by means of wings at the base plates. This configuration allowed for replacement of vertical dampers after yielding.

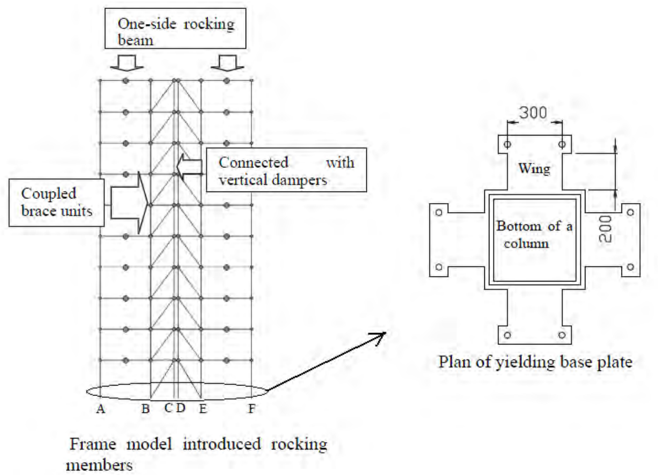


Figure 8 Self-Centering System using Rocking Mechanism [after Azuhata et al. 2008]

Hajjar and Eatherton et al. (2009, 2010, and 2011) examined a steel braced frame with controlled rocking and energy-dissipating fuses. They investigated the behavior of the system and its components, validated the expected performance objectives, studied the limit states and recommended construction details (Ma et al. 2010 and Hajjar et al. 2010, 2011). A number of different types of fuses and different fuse configurations under varying ground motions were tested (Hajjar et al. 2009, 2010 and Ma et al. 2010). They demonstrated the viability of the controlled rocking system as a method of self-centering the entire building via use of hybrid simulation (Hajjar et al 2010); and the cyclic behavior of the components through large-scale testing (Hajjar et al 2011).

As shown in Figure 9, the structure is comprised of dual elastic steel frames allowed to rock about the column bases, vertical post tensioning strands for self-centering, and replaceable steel fuse plates to dissipate seismic energy through yielding. The purpose of this structure is to increase self-centering capabilities, dissipate seismic energy, assure high resilience of the system when subjected to large story drifts, and to use fuses that can easily be replaced after an earthquake.

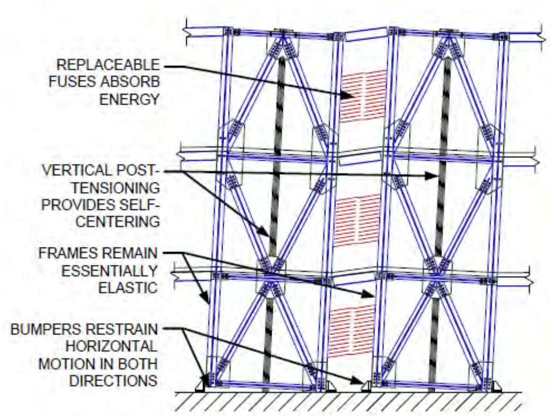


Figure 9 Structural Components of Controlling Rocking System [after Hajjar et al. 2010]

In addition to analyzing the behavior of the controlling rocking system, several configurations of fuses were also examined (Hajjar et al 2009, 2010, and 2011). Fuses were located between two frames or concentrated at the central base of the frames. The work culminated with shake table tests to validate the dynamic response of the system at two-thirds scale (Ma et al. 2010).

The following sections of the report provide more detail about prior research on rocking, self-centering, and energy-dissipating seismic force resisting systems.

2. Structures with Energy-Dissipating Fuses

2.1. Rai, D. C. and Wallace, B. J., 1998

"Aluminium Shear-Links for Enhanced Seismic Resistance"

Introduction:

The paper reviews a study of aluminium shears-links used with structural lateral resistance frames. Aluminium was selected as the link material due to its low yield strength. The link was designed to yield in shear mode and limit the maximum lateral force which would be transmitted to primary structural members. This link also provided significant energy-dissipation. The paper describes the behavior of the shear-link and its role in the structural system through experimental results and a numerical assessment of its seismic performance.

System Concept:

Aluminium was chosen because of its low yield strength and its ability to last through many large plastic deformation cycles before tearing. In shear modes, it can reach greater ductility and dissipate significant amounts of energy. One application of the shear-link is to retrofit chevron-type ordinary CBF. An. The link-beam is designed to yield in shear mode at a lateral force less than that required to buckle the brace in compression. An advantage of this system is that it can carry gravity loads after the link collapse.

Experimental Study, Results and Discussion:

A medium scale of 1:4 was chosen for the experimental testing. The specimens varied in section dimensions, two different alloys of aluminium (3003 and 6061), and arrangements of transverse stiffeners. The purpose of the stiffeners was to delay the initiation of plastic web buckling and improve post-buckling behavior. The specimens were loaded using a sinusoidal input wave with both stress and strain controlled regimes during the experimental testing. The links demonstrated excellent stiffness and energy dissipative capacity over a large range of strains. The softer alloy 3003 is favored due to its better energy dissipation characteristics.

A model of a 4-story building located in the UBC Seismic Zone 4 was created using SNAP-2D. A shear-link braced frame was compared to an ordinary CBF under a static push over analysis and four different ground motions of record. The static push over analysis showed the shear-link braced frame was able to resist additional shear force through a larger deformation as opposed to the ordinary CBF which reduced capacity after brace buckling. The results of the monotonic loading show a reduced base shear, more uniform distribution of story drifts and a larger energy dissipation capacity per unit drift when comparing the shear-link braced frame to the ordinary CBF.

Representative Figure of Structure:

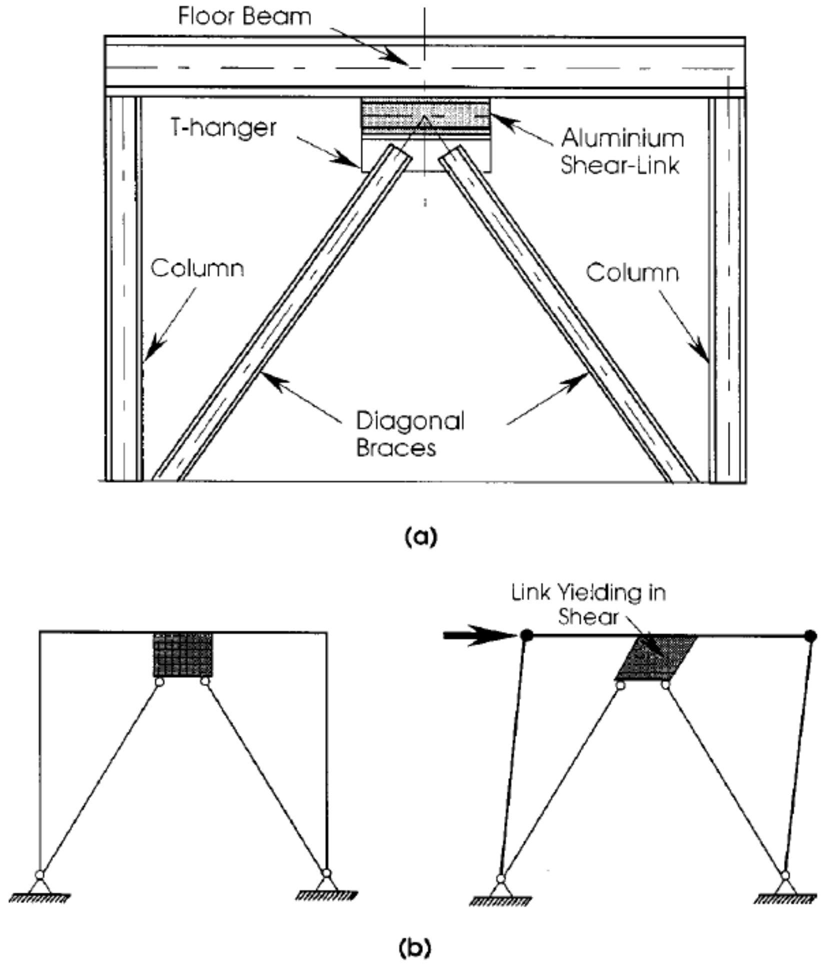


Figure 10 Schematic diagram and typical collapse mechanism [after Rai et al. 1998]

2.2. Cristafulli, F. J. and Restrepo J. I., 2003

"Ductile Steel Connections for Seismic Resistant Precast Buildings"

Introduction:

The response of a connection detail for coupling precast concrete walls in low to medium rise buildings was considered both analytically and experimentally in this research. In this paper, the behavior of isolated connecting plates was experimentally studied in order to investigate the performance of the welded connection.

The connection consists of a rectangular steel plate with a concentric circular perforation. Weak and ductile links are formed and energy dissipation takes place in the connections.

System Concept:

Welded connections are one of the connection approaches to join precast concrete elements. In this research, wall panels were connected through steel plates along a vertical joint. Precast concrete parts were connected to each other by means of perforated steel plates. The weld plates were designed as weak links, so that energy dissipation occurs there, allowing the plates to act as coupling beams.

Experimental Study, Results and Discussion:

Two stiff framed steel plates were used in the test specimen, with two connecting perforated steel plates welded to each face of the framed steel plates. The use of two connecting perforated steel plates was required to obtain a symmetric configuration and avoid out-of-plane movement. A reverse cyclic quasi-static load-displacement test was applied to the specimen to capture some of the features induced by seismic events.

Shear force vs. vertical displacement plots from the test yielded a hysteretic response of the connection. The hysteretic loops were stable and exhibited no stiffness or strength degradation, even though the specimens were subjected to relatively large displacements. Additionally, perforated plates have very ductile behavior. Neither buckling, nor cracking were observed at the maximum ductility level. Extensive yielding was detected in the connections, indicating energy dissipation.

An analytical model with response predictions was created prior to the test, assuming that the fillet welds represent a fixed boundary for the perforated steel plate. However, the experimental results showed that this assumption is not realistic. The experimental value of the stiffness of the welded plate was smaller than that calculated using this hypothesis.

Representative Figure of the Structure:

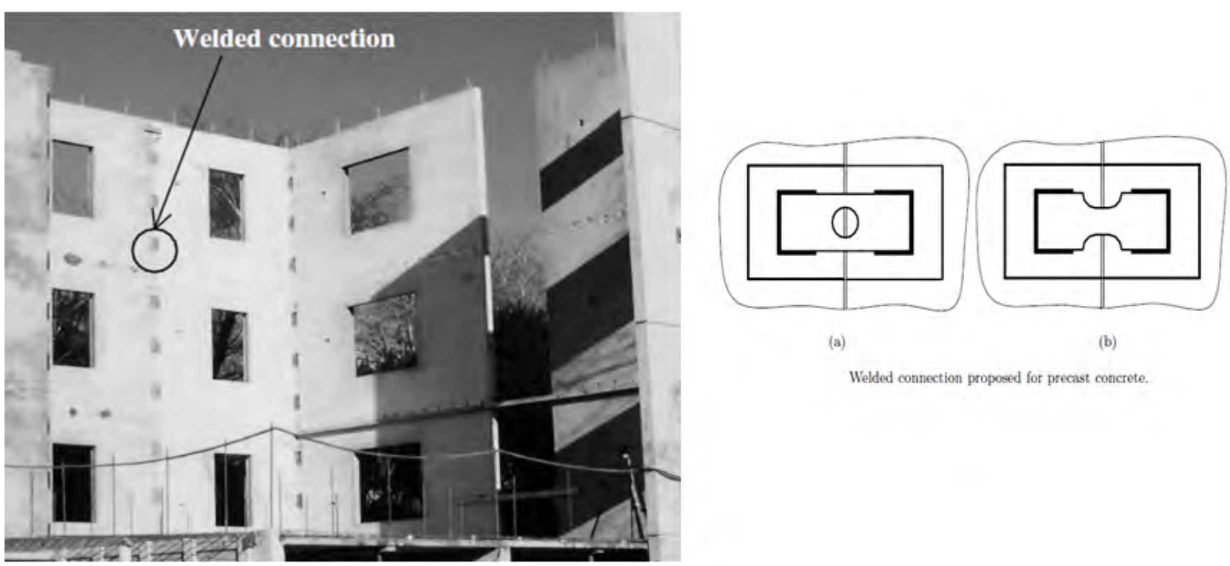


Figure 11 Precast Concrete Walls with Welded Connections [after Crisafulli et al. 2003]

2.3. Krstulovic-Opara, N. and Nau, J., 2003

"Self-Actuating SMA-HPFRC Fuses for Auto-Adaptive Composite Structures"

Introduction:

The authors perform a numerical study on the response of structures with self-actuating fuses. HPFRC is used in conjunction with SMAs in zones of beams with high forces in improve the performance of these regions.

System Concept:

In HPFRCs, fibers are inserted into the concrete mix. This results in the concrete being able to hold tensile stresses, as well as strain hardening after the first cracks appear. SMAs are metals with the characteristic property that they return to their original shape after inelastic deformations through either an increase in temperature provided by a small electric current, or a super-elastic response, in which removal of stress causes the deformation to be recovered.

In both cases, SMAs are able to absorb significant amounts of energy and exhibit self-centering characteristics. This study combines the properties of HPFRCs and SMAs at the ends of beams to create a much more ductile zone where there is a high combination of shear and flexure. HPFRCs and SMAs in this zone or more free to deform than traditional concrete, resulting in ductile beam ends and the dissipation of energy. SMAs are longitudinally pre-stressed, giving them the propensity to return to their original positions. The nature of SMAs (phase changes that occur) allow them to adjust their response to higher capacities as required.

Analytical Study, Results and Discussion:

An analytical study was performed on 5-story reinforced concrete structures with the HPFRC and SMA fuse system and without the system. It was observed that under seismic loading, the fuses were able to absorb the high seismic energy that could not be dissipated by the building without the HPFRC and SMA fuse system. Only the building with the system was deemed repairable after high earthquake loading.

It can be concluded that a self-actuating fuse system has potential for increasing the ductility of buildings under seismic loading, but further research is required in this area of nontraditional building construction. Experimental results still need to verify the effectiveness of the system.

Representative Figure of the Structure:

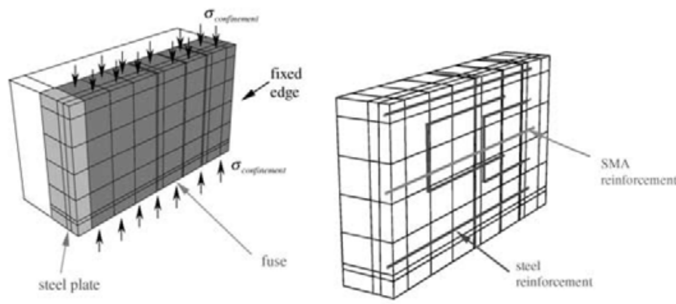


Figure 12 Layout of the Modeled Fuse [after Krstulovic-Opara et al. 2003]

2.4. Bozorgzadeh, A., Megally, S., Restrepo, J., and Ashford, S.A., 2006

"Capacity Evaluation of Exterior Sacrificial Shear Keys"

Introduction:

In this study, the authors assess ten shear keys at bridge abutments with the goal to reduce the input force to the abutment piles by inducing sliding shear failure, making the shear keys sacrificial members. Models were constructed at 1:2.5 scale and excited under a cyclic lateral load. An analytical model was then developed to provide guidelines for the capacity design of shear keys at bridge abutments.

System Concept:

Large diagonal cracks in abutments demonstrated a diagonal shear failure after the Northridge Earthquake in 1994. These shear keys are intended to minimize the force that is transferred to the abutments. Using smooth construction joints at the shear keys and minimizing the reinforcement between the abutment and shear key is intended to allow for motion of the shear key, dissipating energy through the sliding shear failure of the key, and limiting the input force to the abutments.

Experimental Study, Results and Discussion:

Shear keys at 1:2.5 scale were tested in five series. Variables included were the incorporation of a construction joint between the shear key and abutment stem wall, the placement of vertical reinforcement bridging between the abutment and shear key, and the amount of horizontal tie reinforcement. The test mimicked superstructure performance during an earthquake. The abutment wall was posttensioned to a strong floor and a hold down frame prevented a lateral load applied to the shear key from moving upward. Strain gauges recorded movement of the reinforcement and shear key.

It was observed that large cracks occurred in the cases of rough construction joints, indicating a diagonal shear failure. The presence of wing walls was also found to increase the shear capacity. In the test with limited vertical reinforcement, sliding shear failure was observed, with the rest of the tests exhibiting diagonal shear failure. This indicates that smooth construction joints with limited vertical reinforcement will induce sliding shear failure that dissipates energy.

Analytical Study:

A simple analytical model was created to assist in designing the appropriate vertical reinforcement to induce sliding shear failure. The model was calibrated using data backed out of successful tests yielding sliding shear failure through the use of a smooth construction joint and accounting for kinks in the reinforcement resulting from experimentally measured sliding shear deformation.

Representative Figure of the Structure:

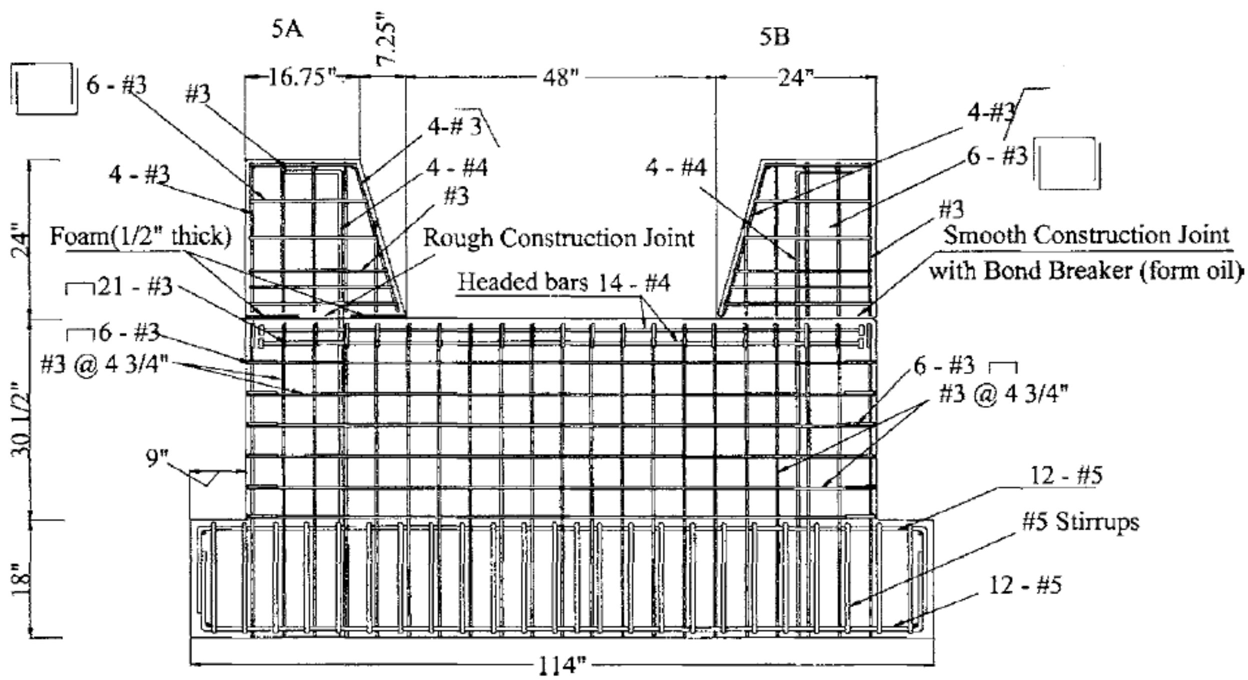


Figure 13 Shear Key [after Bozorgzadeh et al. 2006]

2.5. Iqbal, A., 2006

"Soft First Story with Seismic Isolation System"

Introduction:

This paper proposed a new version of the soft first story with elastoplastic isolation system. The concept of soft first story was explained in order to incorporate seismic isolation system. This enables separation the first story from the rest of the building. Isolation system provides the ductility and energy dissipation during an earthquake. Moreover, a number of systems having different shapes and arrangements were considered in this study and some arrangements showed that the soft first story provides effective protection against seismic forces while maintaining overall stability.

System Concept:

The isolation system was composed of sliding bearings and steel dampers placed between the top of the first story and the rest of the superstructure. It allows for relative displacements between the adjacent elements while reducing the force transmitted to the upper level. Energy is dissipated through yielding of the steel elements.

The chosen arrangement should be stable in normal service condition and for wind loading; and should transfer the vertical load and keep minimum horizontal earthquake force transferred to the stories above.

The arrangement may consist of Teflon-stainless steel sliding bearings and steel dampers assembled in a single device.

Implementation:

Problems with implementing the system on the ground floor include spaces have to be kept for movements, services have to be made flexible, underground water reservoir would need to be located above about the isolation level and additional attention to sub ground machinery and parking is necessary. Many of these special provisions can be avoided by installing the system on the top story.

Representative Figure of the Structure:

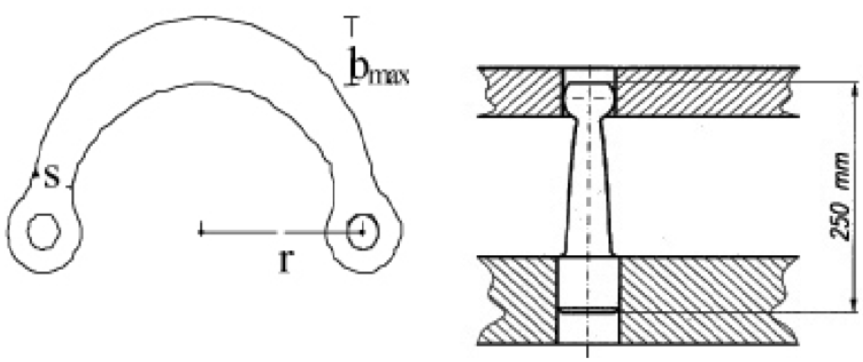


Figure 14 Steel crescent moon-shaped and pin dissipation elements [after Iqbal et al. 2006]

2.6. Smith, R.J. and Willford M.R., 2007

"The Damped Outrigger Concept for Tall Buildings"

Introduction:

In this paper, a new philosophy for the design of high-rise buildings with damped outriggers was presented. The dynamic response of a tall building has generally been governed by structure shape, stiffness, mass and damping. The first of three of these inputs are much easier to assess. The effect of shape can be evaluated by wind tunnel testing. Moreover, the mass and stiffness can be predicted the structural designer. However, the available guidance for damping of tall buildings, used primarily to reduce dynamic wind effects, shows huge variance. This is especially compounded by the difficulty of measuring damping experimentally. The authors, therefore, outline design procedures, approaches and a design example for damped outriggers.

System Concept:

Viscoelastic dampers were attached between two points on a structure damping response based on the relative motion between the two points. The best location for this device was two points that had significant relative displacement. Dynamic sway induces large relative vertical motion between the perimeter columns and the ends of stiff outrigger elements cantilevering from the core, offering an excellent location for the viscoelastic damper. A damper was inserted across this structural discontinuity, dissipating energy during the cyclic motion, and resulting in an increase in the overall damping of the building. It was necessary for the outrigger element to move vertically relative to the floors at these levels, while the floors bent in double curvature to remain connected to the core and the outer columns.

Results and Discussion:

The authors recommend that designers first determine the required stiffness and damping for their structure. Then damping should be estimated, followed by selection of a damping system and optimization of structural stiffness.

This system has economic advantages over conventional damping mechanisms. In addition to significant economic savings, increased damping and stiffness, this system results in a favorable response to cyclic motion. By means of the lateral stiffness of a high-rise structure, the element sizes and material content can be reduced.

Representative Figure of the Structure:

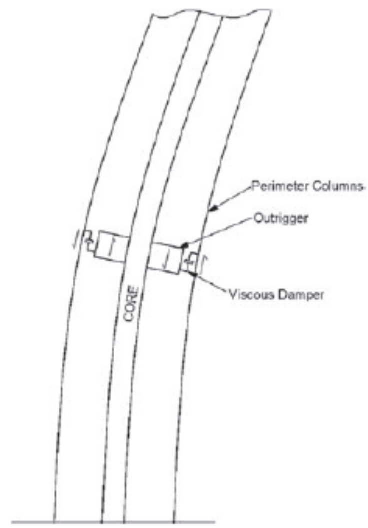


Figure 15 High-Rise Buildings with Damped Outriggers [after Smith et al. 2007]

2.7. Aliaari, M. and Memari, A.M., 2007

"Experimental Evaluation of a Sacrificial Seismic Fuse Device for Masonry Infill Walls"

Introduction:

The authors examined an infill wall fuse system with the goal in mind to prevent damage to the columns and infill walls. This device is known as a SIWIS. Sacrificial disks made of steel, concrete, and timber were tested and compared to determine which was most adequate as a fuse element.

System Concept:

Structural fuse elements are located in the gaps between the infill walls and the frame structure. As a lateral load is applied, the fuses are engaged, and are designed to yield before the frame or infill wall yields. The yielding of the fuse disks acts as an energy-dissipating mechanism. A punching rod is placed next to the disks as a rigid element to help fail the fuse.

Experimental Study, Results and Discussion:

Three structures were tested in this study: a two-bay 3-story frame of bare steel, infilled brace frame, and pinned frame with the SIWIS. Component tests were also conducted to determine the failure stresses and strains of disks made of concrete, steel, and lumber. A lateral load in-plane strength test was also conducted on a single-layer masonry wall to determine the in-plane strength of the wall. This was done so that the fuse could be designed to fail before the wall.

The three disk types were compared with disks of similar capacity to determine the relative stiffness of the potential energy dissipaters. It was found that the steel and concrete disks were less ductile than the lumber disk. The lumber disk experience less of a drop in resisting load after the peak load. These results led to the use of lumber disks in the two-bay 3-story frame test.

The test frame was built as a 1-4 scale model with pinned beam to column and column to column connections. Testing occurred on a bare steel frame, an infill frame with diagonal bracing, and an infill frame with SIWIS elements. It was found that if an SIWIS (timber disk) fails at the point of load application (the third story), the resistance of the system drops to zero since there is no in-plane resistance. The punching rod can punch through and fail the disk. The frame fails without interaction with the masonry wall panels. This experiment showed that having properly designed SIWIS can produce interaction between the masonry infill wall and a frame, increasing the in-plane strength of the system.

Representative Figure of the Structure:

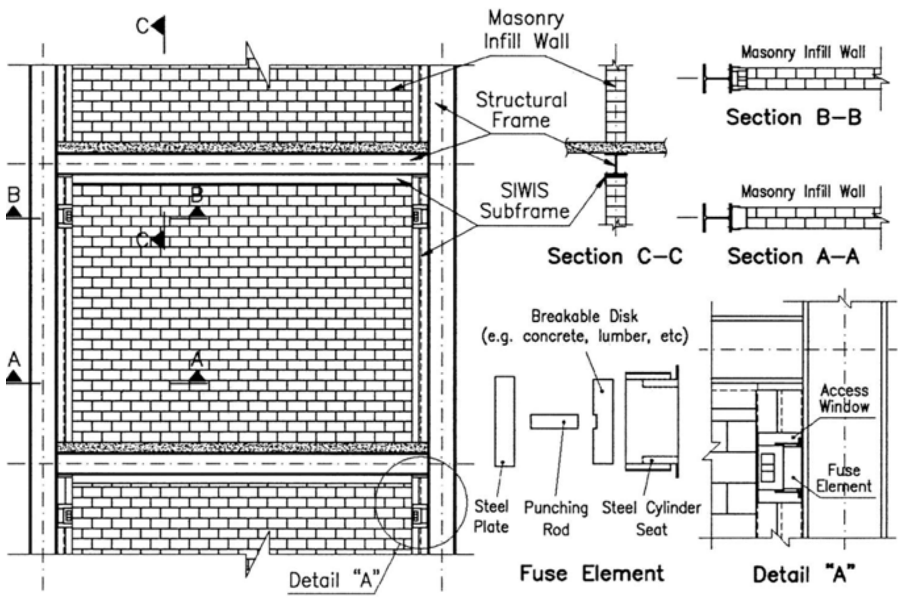


Figure 16 SIWIS System in Building Frame [after Aliaari et al. 2007]

2.8. Fortney, P.J., Shahrooz, B.M., and Rassati, G.A., 2007

"Large-Scale Testing of a Replaceable "Fuse" Steel Coupling Beam"

Introduction:

The authors conduct large-scale cyclic tests on a coupling beam between core walls with a replaceable element at the midspan of the beam. Coupling beams are intended to form hinges prior to hinges at the base of wall piers. This study attempts to form these hinges in specific, easily replaceable identifiable and replaceable zones.

System Concept:

The goal of this experiment is the concentrate yielding in a specific, replaceable region. The midspan of the coupling beam (already set to form hinges prior to the base of wall piers) is ideal because it is often much more easily accessed than other parts of a structure. The fuse at the center of the beam is the same section as the main portion of the coupling beam, but with a thinner web, so as to induce yielding in a specific location.

Experimental Study, Results and Discussion:

Coupling beams are embedded in wall piers. The main section is connected to the fuse section through a slip critical connection with web and flange splice connections. Test specimens were loaded with increasing amplitude in a reverse cyclic fashion. Tests were performed on specimens with the fuse section at 50% and 70% of the shear capacity of the main section of the coupling beam. These tests were compared to those of a steel coupling beam without the fuse element at its midspan.

In the traditional steel couple beam, little damage was observed in the piers, indicating a sufficiently ductile connection to the wall piers. The steel coupling beam with a fuse element at the midspan experienced early energy dissipation and low stiffness. Weld fractures also occurred after the beam reached 5% chord rotation.

The authors recommend that the fuse be designed for the ultimate shear forces so that it can withstand expected shear forces, and that the rest of the coupling beam be designed as a larger member.

Representative Figure of the Structure:

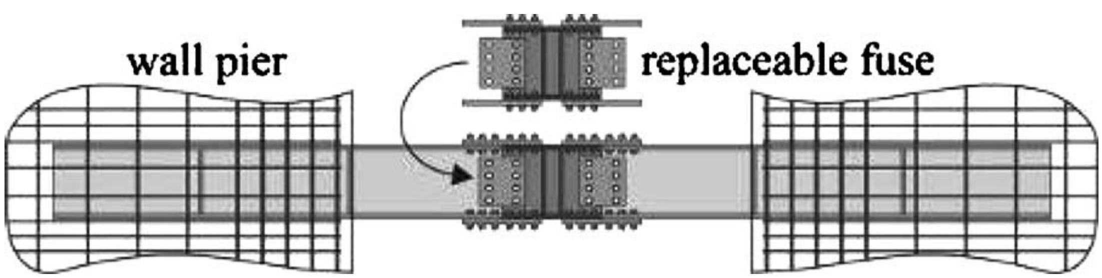


Figure 17 Schematic of Steel Coupling Beam with Replaceable Fuse Element [after Fortney et al. 2007]

2.9. Kassis, D. and Tremblay R., 2008

"Brace Fuse System for Cost-Effective Design of Low-Rise Steel Building"

Introduction:

Braced fuse systems for low-rise steel buildings and its design procedure were presented in this paper. Design and performance of the braced fuse system were explained in light of tests. A parametric study was also performed to show that the use of braced fuses results in cost reductions when compared to T/C braced frames.

System Concept:

This system has been developed for braces made of rectangular or square structural tubing. The braced fuse systems were used to keep the braces in tension during ground motion, allowing for an increase in design forces. The fuses are located near the brace end. Rectangular or square structural tubing was used for this fuse system. The tubes were cut at the fuse locations and four angles were used to connect the two tube segments. These angles are located along each of the four corners of the tube cross section and welded to each of the two brace segments. Unfortunately, these braced tension fuse systems are not replaceable, since welded connections are used.

Experimental Study, Results and Discussion:

The results from full scale quasi static cyclic tests performed to verify the performance of the braced fuse systems for low-rise steel buildings are presented. The results of quasi-static cyclic tests verified the seismic performance of the system and the effects of brace fuse systems on force demand in low-rise steel buildings. From test results, it is concluded that adding brace fuses in T/C to moderately ductile MD braced frames is an effective way to reduce the connection tension design loads.

Parametric Study:

Parametric study was performed to evaluate the benefits of using the proposed brace fuse design. Rectangular single story steel structures with different plan areas and different plan aspect ratios were used for this study. MD and LD braced steel frames with and without brace fuse systems were designed and compared. According to the results, MD designs were more effective than LD type. Moreover, adding brace fuses in T/C type MD brace frames was the best solution for reducing the connection tension design loads.

Representative Figure of the Structure:

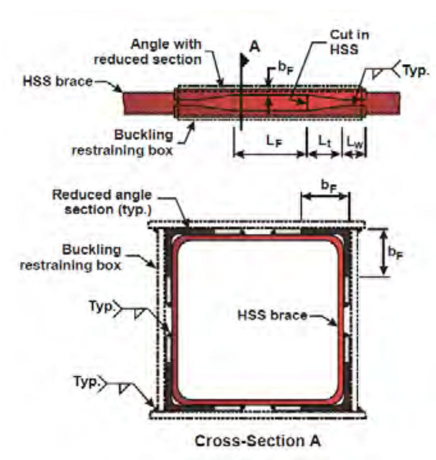


Figure 18 Braced Fuse System [after Kassis et al. 2008]

2.10. MacRae, G.A., 2008

"A New Look at Some Earthquake Engineering Concepts"

Introduction:

In this paper a number of issues related to the design of structures subjected to earthquake excitation were explained. Slab effects on moment frame joints, slab overstrength effects on steel moment connections, low cost damage free steel joints, the quantification of drift concentrations in steel framed structures and the quantification of building torsional effects by means of impulse loading were discussed.

System Concept:

For SHJs, the beam top flange is connected to the column by means of a top flange plate; therefore rotation of the beam end occurs about the connection of the top flange plate to the column flange. The shear force in the beam is carried by the top web bolts. Horizontally slotted holes are provided in the bottom flange plate and in the bottom of the column web plate to allow significant rotations of the beam end relative to the column face.

DSFDs can be used within or at the end of the braces to dissipate energy. In the connections between gusset plate to beam and floating plate to brace, elongated bolt holes were used, providing large deformation capacity. This system experiences no significant damage, with the same properties in each direction. Moreover, the system is able to self-center and the bolted floating plate can be replaced after yielding.

Results:

SHJs can dissipate energy and be replaced after yielding more easily than other fuse systems; moreover, DSDFs foster a damage-free system with SCs and can also be replaced.

Representative Figure of the Structure:

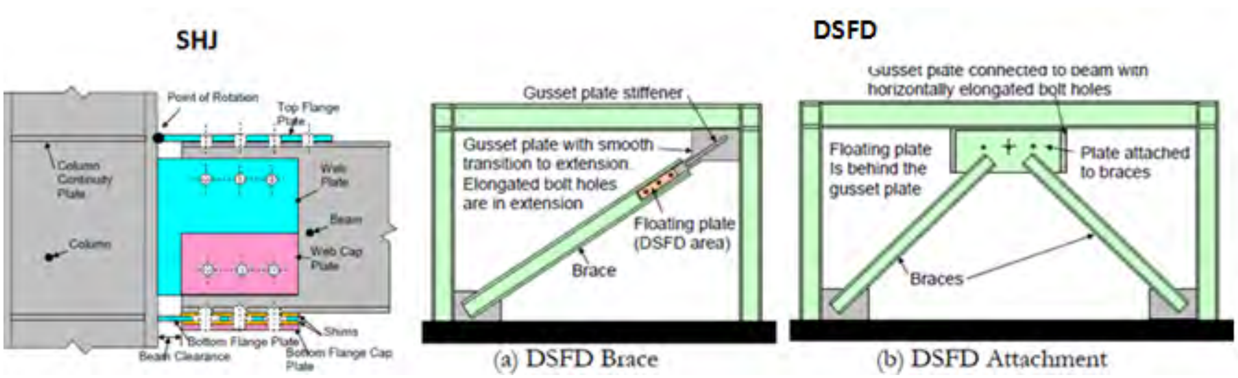


Figure 19 SHJ and DSFD [after MacRae et al. 2008]

2.11. Patro, S.K. and Sinha R., 2008

"Optimal Seismic Performance of Friction Energy-dissipating Devices"

Introduction:

In this paper the optimal seismic performance of friction devices, in order to reduce the response behavior of frame buildings, were numerically investigated. The design of the friction based passive energy dissipation devices was based on numerical simulation with constant coefficient of friction. Due to the non-linear relationship between dry friction and sliding velocity the writers investigated the energy dissipation devices with stiction and Stribeck effects the in friction model. Moreover, the response of 4-story example frame building with friction devices were investigated and discussed in terms of various dimensionless performance and optimal seismic performance of friction devices.

System Concept:

The structure for the mathematical formulation was considered as a two dimensional shear building. Two degrees of freedom were used for each floor, corresponding to the horizontal displacement for the story and the brace. Simple friction energy dissipation devices were connected to the centerline of the beam soffit. Beam weight and loading does not have any effect on the sliding surface. The sliding plate has slotted holes and is sandwiched between two clamping plates with pre-stressed connection bolts. The slotted holes facilitate the movement of the sliding plate over the frictional interface at a constant controllable pre-stress force. The placement of sliders in the vertical plane of the beam guarantees that only the pre-stress force controls the normal load on the sliding surface. The presence of two friction interfaces for each bolt doubles the friction resistance.

Numerical Study:

In order to idealize the dynamic behavior of the structure, two lumped mass models were used; on for the free frame structure and another for the brace with device. From entire solution process, the equations of motion were split into two subsets; non-sliding phase and sliding phase.

In order to characterize the seismic efficiency of friction devices, six dimensionless performance indices have been considered; displacements, acceleration, base shear, strain energy, input energy, and dissipated energy. The various performance indices were evaluated for realistic friction model. Values close to zero indicate excellent performance of the friction devices in reducing the response while values close to 1 or higher indicate ineffectiveness of the friction devices. According the results, pre-stress force is the most important parameter for the design of the friction devices.

Representative Figure of the Structure:

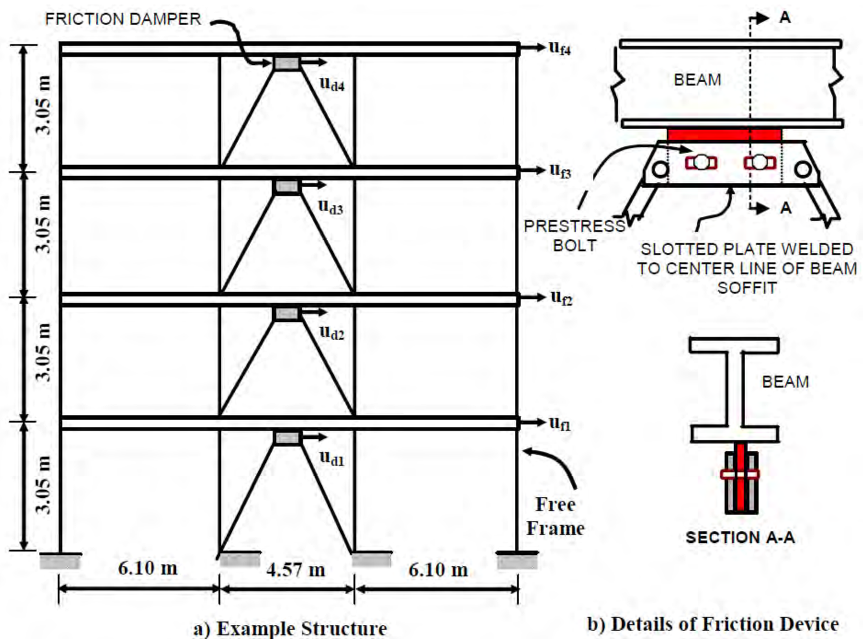


Figure 20 Schematic Diagram of 4-Story Building with Friction Devices [after Patro et al. 2008]

2.12. Ruangrassamee A. and Mounnarath P., 2008

"Monotonic and Cyclic Behaviors of Energy-Dissipating Threaded Mechanical Splices"

Introduction:

In this paper the study related with energy-dissipating threaded mechanical splices were investigated from the results of tensile, compressive and cyclic tests. The proper connectors between the precast structures were developed for application in seismic regions, due to the inadequate seismic response of precast structures. These proper connectors had to exhibit sufficient strength, ductility and energy dissipation capacity.

System Concept:

The mechanical splices are used to connect bars to transfer tension or compression forces. Therefore, couplers in mechanical splice systems have the tension strength larger than that of reinforcing bars. The coupler acts as a fuse in a column to absorb energy, therefor it could be used in the construction of precast structures, especially in precast columns.

The spice is composed of a hollow steel coupler threaded throughout its length and two reinforcing bars with threads at their ends. The coupler is designed to fail with sufficient energy dissipation; moreover, the amount of energy dissipation at the coupler is controlled by the coupler thickness and the gap length.

In compression, the mechanical splices exhibit higher compressive strength with more post-buckling resistance than the plain control bar. In addition, the energy dissipation of the splice is 5 times the plain bar. In tension, the maximum load is close to the capacity of the coupler; the energy dissipation of the mechanical splices increases when the coupler gap length increases. However, the ductility of plain bars is approximately 5 times the ductility of the splices in tension.

Experimental Study, Results and Discussion:

In the tests, the thickness and gap size of the coupler were varied. The thickness controls the yielding force level and the length of the gap size controls the deformation capability of the coupler. Monotonic tensile test, monotonic compressive test and cyclic loading test were performed for the specimen.

A monotonic tensile test was performed in order to find out the optimal parameters of the mechanical splice that caused failure at the coupler with the largest energy dissipation. From results, it was seen that as the thickness of the coupler increases, the load resistance of the splice increases. From monotonic compressive test, it was found that the energy dissipation of the splice with a coupler gap was approximately 5 times the energy dissipation of the control bar, and the maximum load capacity of the splice was greater than that of the control bar. From cyclic loading test, load-deformation relation was obtained and, according to the results, load dropped dramatically after buckling by about 40% of the peak load.

In summary, the load resistance of the mechanical splice is controlled by the coupler thickness while its ductility is controlled by the coupler gap lengths, the splices exhibit higher resistance in compression after buckling and the energy dissipation of the mechanical splice in the cyclic test increases as the gap length increases.

Representative Figure of the Structure:

Figure 21 Assembly of Mechanical Splice Used in the Study and Test Set-Up [after Ruangrassamee et al. 2008]

2.13. Bo, L. and Xingwen L., 2008

"Seismic Design of Structure with Improved Toggle-Brace-Damper System"

Introduction:

This paper introduced the TBD system and its installation configuration. Equivalent damping ratio and a simplified procedure for design and analysis of building incorporating TBD systems were proposed. The authors then introduce an expression for prediction of equivalent linear viscous damping ratio provided by the improved TBD systems installed in a building. Finally, validity of the design method was verified by a nonlinear RHA

System Concept:

The purpose of this system is for energy dissipation devices to consume the input energy to the system, so that damage to the main structure is reduced or eliminated. Viscous liquid dampers are one of many energy dissipation devices, and have been used for this purpose in both new and existing buildings. This system suffers from lowered efficiency of energy dissipation due to the low axial displacement when compared to story drift. This problem can be solved by using larger size dampers or amplifying the displacement and velocity in the damper. Larger dampers result in high cost for building rehabilitation, thus increasing the displacement and velocity of the damper is preferred. The TBD system can thus be useful as it creates device displacement larger than the structural drift.

The TBD is directly connected to the beam in a classic configuration. The displacement amplification factor may be smaller than expected due to the flexibility of the beam. In order to overcome this issue, the damper and brace elements were connected directly to the beam-column joints, in the configuration for upper damper and lower damper. So the RHA was conducted on buildings installed with improved upper TBD, lower TBD, and buildings with diagonal brace dampers to compare the efficiency of vibration control for different configurations of energy dissipation devices.

Design Procedure:

In the calculation of equivalent damping ratio for structures with lower and upper configuration of TBD system, the magnification factor was derived based on the assumption of small deformations and an axially rigid brace. Based on the Chinese design response spectrum, the effective damping ratio was determined. Then this ratio was used to limit the roof displacement of the damped structure to a specified value.

After outlining design steps, an illustrative example was presented to design and analyze a building with improved TBD systems. The response quantity of interest of the damped structure obtained by the proposed method and the mean results obtained by nonlinear RHA of the designed structure under the artificial ground motions were compared to verify the validity of the proposed method. Finally, nonlinear RHAs of buildings installed with improved upper TBD, lower TBD, and the diagonal brace dampers were conducted in order to compare the efficiency of vibration control for different configurations of energy dissipation devices.

As a result, improved upper TBDs were found to more effectively reduce the floor displacements and story shears demands than improved lower TBDs and diagonal brace dampers.

Representative Figure of the Structure:

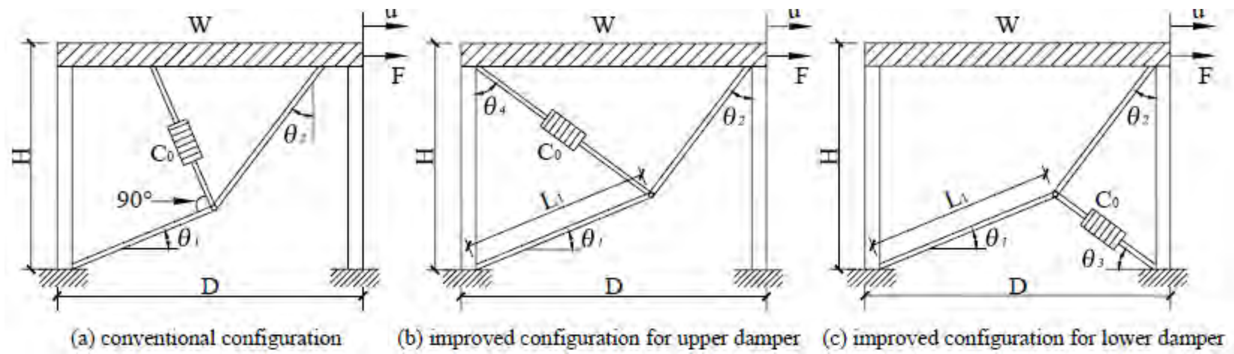


Figure 22 Installation Configuration of the TBD System [after Bo et al. 2008]

2.14. Dicleli, M. and Mehta, A., 2009

"Seismic Retrofitting of Chevron-Braced Steel Frames Based on Preventing Buckling Instability of Braces"

Introduction:
The authors propose and perform an analytical study of a retrofit to a chevron braced frame. An energy-dissipating element is placed between the braces and the connecting beam. Nonlinear static pushover, time-history, and damage analysis are conducted and the results compared between a chevron braced frame and the retrofitted chevron braced frame. The energy-dissipating element can either be an HP or W section.

System Concept:

The goal of this system is to prevent the buckling of the braces by yielding another element first. The HP section at hand is composed of stocky plates that can undergo large inelastic deformations and failing in shear from the axial forces of the braces. The system is meant to be replaceable so that the existing structure is not affected. With this is mind, it is important that the fuse element take most of the energy so that the rest of the structure does not experience any buckling or damage.

Analytical Study, Results and Discussion:

The authors performed an analytical study of this system including buckling instability of the braces. The behavior of the system with the braces as the main energy-dissipating system is compared to the system with the fuse element connecting the braces to an overhead beam as the main energy dissipater.

Imperfections are introduced into the brace model to allow for buckling. The analytical study examined the systems with varying numbers of stories, as well as brace slenderness, to see what roles these played in the energy-dissipating abilities of each system.

It was found that adding fuse elements reduces the brace sensitivity to slenderness, preventing the braces from buckling. It was also found that the lateral strength of the frame is maintained because the braces do not buckle, when the fuse element is added to the brace connection.

It is noted that the fuse elements are much more effective with low levels of ground motion and low number of stories. The fuse elements do not go far past yielding with high motions, although inter-story drifts are still only 60% of the chevron braced frames without fuse element retrofits. These can be attributed to the combination of elastic stiffness of the braces with the energy-dissipating capabilities of the fuse elements.

<u>*Representative Figure of the Structure:*</u>

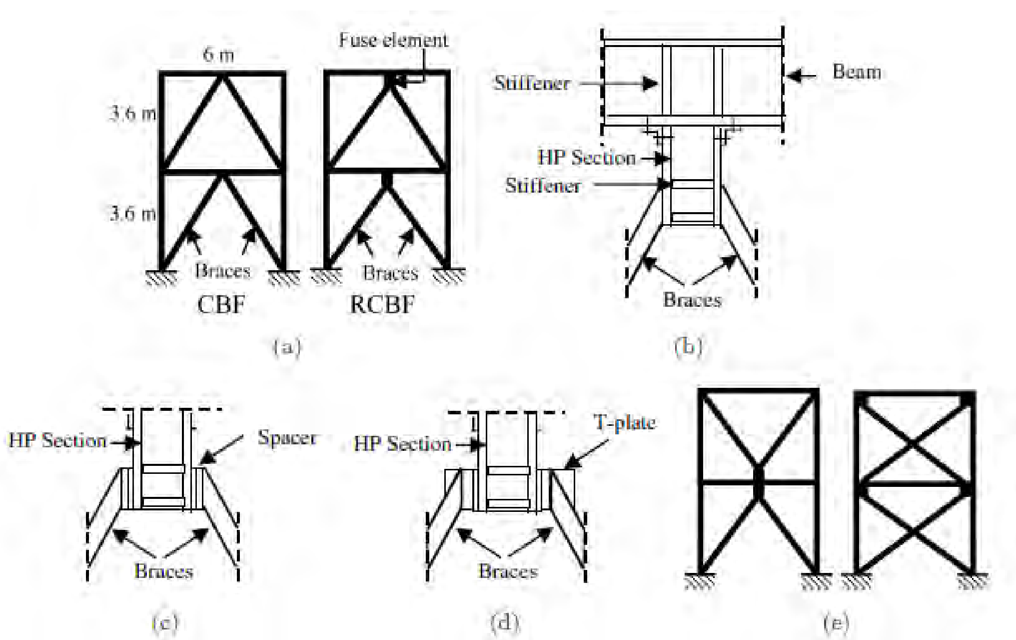


Figure 23 Details of (a) 2-story CBF and RCBF, (b) fuse element and connections in the RCBF, (c) connection of braces to the FE using spacers, (d) connection of braces to the FE using a T section, (e) other brace configurations [after Dicleli et al. 2009]

2.15. Farrokhi, H., Danesh, F., and Eshghi, S., 2009

"A Modified Moment Resisting Connection for Ductile Steel Frames (Numerical and Experimental Investigation"

Introduction:

The authors perform and experimental an analytical assessment of reducing the cover plate section and drilling holes in cover plates at beam to column moment connections. Three full scale connections were tested under seismic loading.

System Concept:

Reducing the cover plate section and drilling holes in the cover plates are intended to prevent failures at stress concentrations at the welds in connections. It is optimal to achieve plate yielding to weld fracture. The cover plates become a structural fuse as stress concentrations that occur from drilled holes induce plate yielding prior to weld fracture. Yielding cover plates instead of breaking welds serves an additional purpose of being a much easier component to replace.

Experimental Study, Results and Discussion:

Three connections were tested in this experiment: one unchanged connection, and two with cover plates with drilled holes. In the unchanged connection, cracks propagated from the weld roots and there was a significant decrease in stiffness and strength under cyclic loading. The two samples with drilled holes in the cover plates showed consistent hysteretic behavior without as significant a loss in stiffness and strength. It was also observed that connection rotation was greater at the modified connection with drilled holes.

These results indicate that the modified connection is indeed shifting stress concentrations from the welds to the cover plate around the drilled holes, producing a much more ductile connection. This connection can alleviate worries about the quality of the weld roots.

Analytical Study:

An analytical study via finite element modeling was performed to examine the effects of certain parameters on the behavior of the connection, namely: cover plate thickness, end plate thickness, the number and diameter of drilled holes, the quality of the weld roots, and other previously studied factors having to do with the geometry of adjacent members.

It was found that the cover plate thickness has a large impact on the stiffness of the connection. The end plate connection has an impact on the stiffness, but does not significantly impact the strength capacity of the connection. It was found that large holes and large numbers of holes both precipitate premature yielding of the connection. The authors recommend that the hole diameter be limited to 0.8 times the cover plate thickness and that the clear distance between the holes be at least 1.25 times the plate thickness.

Representative Figure of the Structure:

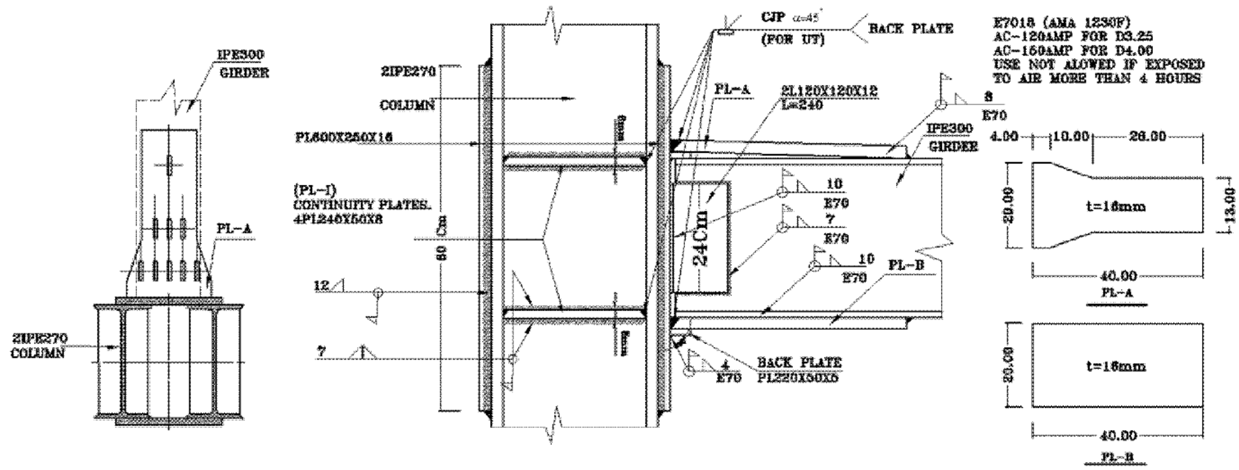


Figure 24 Schematic Design of Cover Plate Connection [after Farrokhi et al. 2009]

2.16. Gray, M., Christopoulos, C., and Packer, J., 2010

"Cast Steel Yielding Fuse for Concentrically Braced Frames"

Introduction:

Steel castings have predominately been used in modern times for aesthetic appeal due to the freedom of geometry offered. Recently in the design of seismic resisting steel structures, steel castings have gained interest for the potential to simplify design and detailing of complex structural problems. The proposed cast steel connectors are designed to act as the ductile yielding fuse element in a concentrically braced frame.

System Concept:

The system is designed to achieve a stable symmetric inelastic response through the flexural yielding of specially designed fingers. Unlike a BRB, the cast steel fuse is a connector that fits to the end of a standard structural shape and is intended to be readily available. The cast steel fuse is engaged by the later force resisting system during a seismic event. Energy dissipation happens through the flexural yielding of the specially designed fingers.

The fingers have been shaped to induce flexural yield along most of their length to maximize ductility. The bending and shear force diagrams of the fingers are similar in nature to a cantilever. An even distribution of plasticity occurs as the finger yields due to the nearly constant curvature along the length during deformation.

Experimental Study:

A full scale prototype was designed, manufactured, and tested under cyclic, quasi-static axial loading with a universal testing machine. The prototype was created to represent the second floor brace of a 6-story steel building located in Los Angeles. Following ANSI/AISC procedures, the system was loaded based on the qualifying protocol for buckling restrained braces.

Preliminary results showed significant energy dissipation capacity. It was noted that the purely axial load test described is not a direct representation of the boundary condition of a brace in the assembly of a real building frame. The expected stiffness, strength and ductility responses of the device were confirmed by the prototype.

Representative Figure of the Structure:

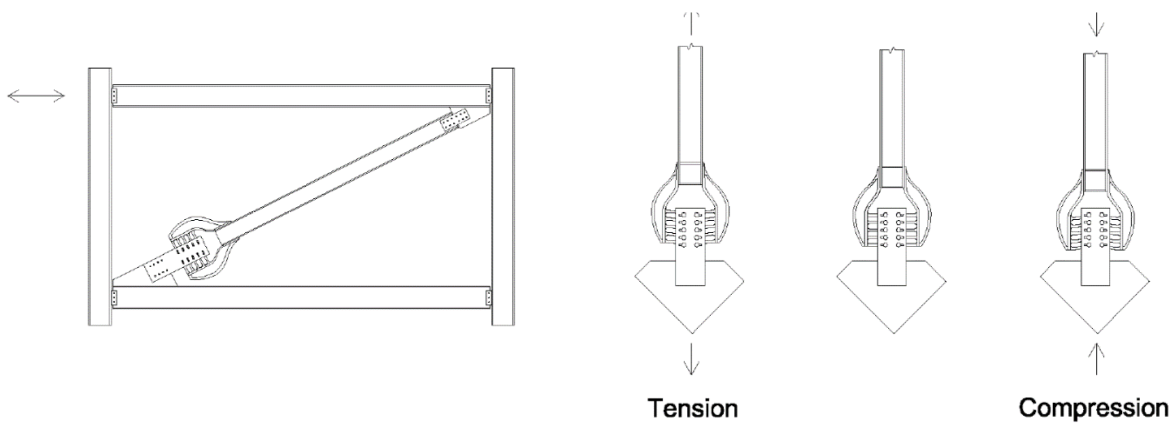


Figure 25 Deformed shape of a yielding CSF-brace assembly [after Gray et al. 2012]

2.17. Kasai, K., Ito, H., Ooki, Y., Hikino, T., Kajiwara, K., Motoyui, S., Ozaki, H., and Ishii, M., 2010

"Full-Scale Shake Table Tests of 5-Story Steel Building with Various Dampers"

Introduction:

This paper discusses the results from a full scale study of the effect of various dampers and isolation systems in a steel frame building. The testing took place at the E-Defense shaking table facility in Japan. The objective was to validate the reliability of the passive control technology through realistic experiments.

System Concept:

The 5-story MRF consisted of 12 dampers of the same type with three to four different sizes. The five categories of primary dampers examined were viscous, oil, viscoelastic, steel, and friction. A steel, oil, viscous, and viscoelastic damper were experimentally tested for this research project. The building was tested repeatedly with the damper type being replaced for each damper type due to economic reasons. The excitations simulated were a DBE, maximum considered earthquake acceleration, the JR Takatori Ground Motions, and a 5% Damping Ratio.

Experimental Study, Results and Discussion:

The quantities which were measured included strains, deformations and displacements, 3D-Accelerations, pressure between ceiling edge and partitions, ceiling hander reactions force, and motion records outside and inside the building. Experimental measurements were compared to previous analytical predictions.

Story shear based on inertia forces and story shear based on member forces was found to match the predicted values well. The hysteresis curves showed significant energy dissipation and the story drift angle was found to be under the 1% radian design target value. These peak responses were compared with the buildings response without dampers and were shown to be considerably less. The analytical analysis proved to match up well with measured recorded damper force.

Representative Figure of Structure:

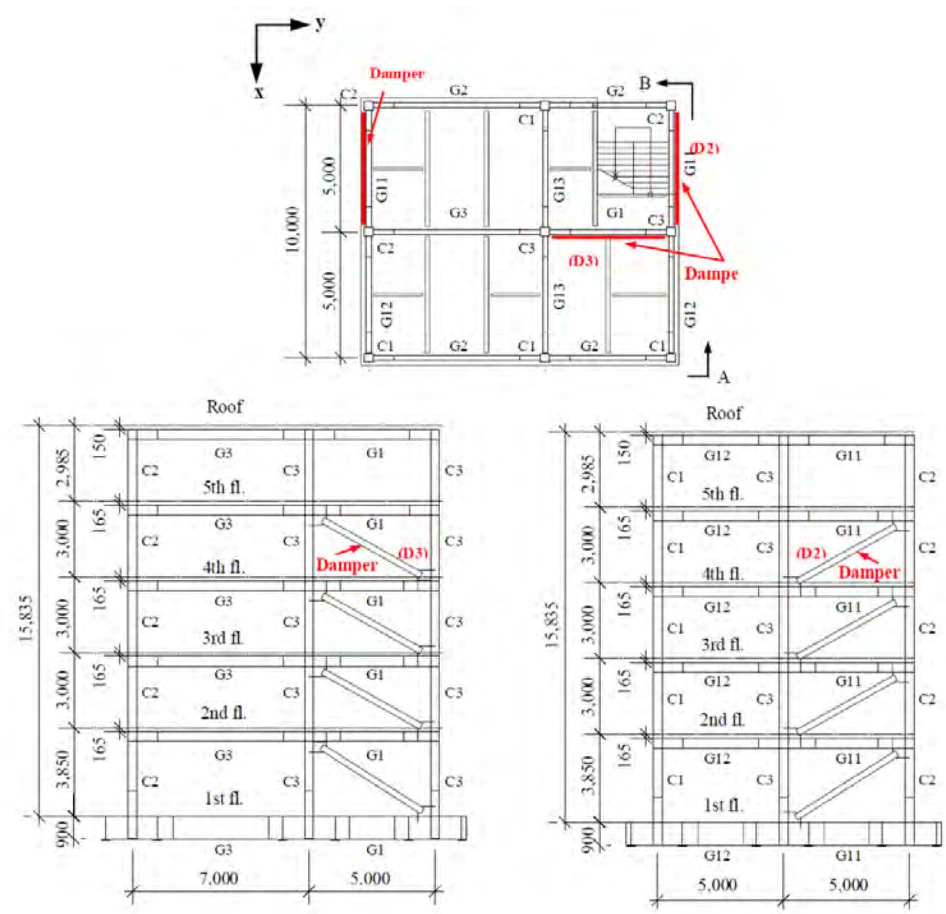


Figure 26 Plan and elevation view for full scale 5-story specimen [after Kasai et al. 2010]

2.18. Chen, H. T., Su Y. F., and Tang H. H., 2011

"The Seismic Responses of 14-Story RC Structures Installed with Three-Pin Steel Damper"

Introduction:

The purpose of using dampers is to dissipate input energy to the system and avoid inelastic behavior of the primary structural members. This paper explains a new type of damper called the three-pin steel damper. In order to investigate the effectiveness of the developed damper, the nonlinear dynamic responses of designed RC structures with the damper are examined. The experiments show that the energy dissipation mechanism was stable with a large area of hysteresis loops. It can also eliminate the defects of the X type and the triangular type steel damper, called ADAS.

System Concept:

Dampers use the stable hysteretic behavior of steel to dissipate input energy. ADAS is a mechanical device made of steel plates with an X or triangular shape and assembled with bolts and/or welds to end blocks. The top of this damper is connected to a girder when the end block is attached to the brace members. In this paper, a new type of damper, a three-pin steel damper, was developed to install on a separate wall within a panel. The three-pin steel damper has hinge-type connections, so that it can be easily produced. Two types of three-pin steel damper were developed. The general difference was the location of intended failure. The Type A damper was designed to ensure that the steel damper remains elastic and the breakage occurs at some distance from the center pin. The Type B damper was designed to let the plastic zone be developed near the center pin, and the breakage extends from the edge of the steel damper to the center pin.

Experimental and Analytical Study, Results and Discussion:

For Type A and B dampers the displacement-control cyclic tests were performed for different displacements; it was seen that the number of cycles leading to failure decreases with increasing displacement.

In the analytical study, a 14-story reinforced concrete building was designed to investigate the effectiveness of three-pin steel dampers. To install the three-pin steel dampers within a panel, a wall-type column was constructed between the top and bottom of beams and cut into two pieces a distance of 500mm apart vertically which was used for the installation. In order to obtain a relation between the story shear and the story displacement, a pushover analysis was conducted.

As a result, the maximum reduction in story ductility ratio is 70% and that in story drift ratio is 54%, so the use of developed dampers was effective in reducing the seismic responses.

Representative Figure of the Structure:

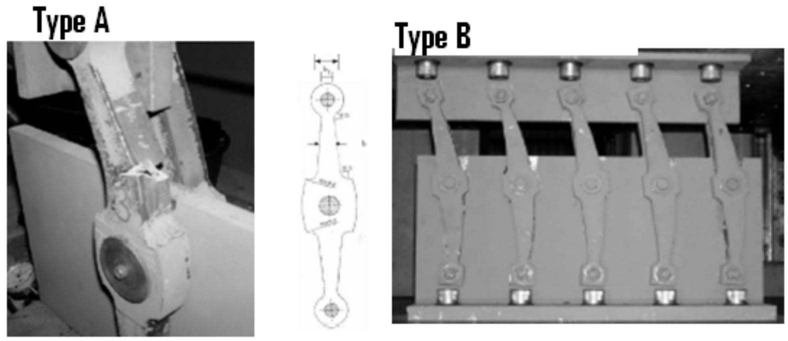


Figure 27 Three-Pin Steel Dampers [after Chen et al. 2011]

2.19. Kim, J., Choi H., and Min K.W., 2011

"Use of Rotational Friction Dampers to Enhance Seismic and Progressive Collapse Resisting Capacity of Structures"

Introduction:

This paper explains a combined system of rotational friction dampers, which are connected to high strength tendons to improve both seismic and progressive collapse-resisting capacity of existing structures. The writers discuss supplemental damping in conjunction with appropriate stiffness, which is an economical solution for the seismic rehabilitation of structures when compared to conventional methods, like concrete shear wall and rigid steel frame bracing. Friction dampers are considered one of the most efficient energy absorbing devices that can be installed in structures to resist earthquake loads.

First, installation of friction dampers is explained, followed by the design and analytical model of a sample structure. Finally, the paper discusses collapse performance of retrofitted structures.

System Concept:

In these friction dampers, two side plates and two circular friction pad discs are placed in between steel plates. The central plate is attached to the girder midspan in a framed structure by a hinge and the ends of the two side plates are connected to the members of an inverted V-brace. In order to avoid compression stresses and subsequent buckling, the bracing includes pretensioned bars. The bracing bars were pin-connected at both ends to the damper and to the column bases. The combination of two side plates and one central plate increases the frictional surface area, while also providing symmetry needed for obtaining plane action of the device. The bolts control the compression force, applied on the interfaces of the friction pad discs and steel plates. The girders displace horizontally when a lateral force is applied to the structure. In other words, when the structure undergoes lateral deformation, the friction dampers are activated and start dissipating energy. The forces transferred through the structure can be reduced considerably by means of dampers; since the dampers dissipate a major portion of the seismic energy.

Analytical Study Results and Discussion:

Design procedures were determined by considering the required effective damping ratio and the frictional moment of the friction damping device. In order to validate the design process of the dampers, 3, 6 and 15-story reinforced concrete model structures were designed considering only gravity loads in OMRF and with seismic loads included in SMRF. OpenSees was used for the analyses.

Nonlinear dynamic time-history analysis results show that the structures retrofitted with rotational friction dampers generally satisfied the given performance objectives under seismic loads. It was observed that the displacement responses decreased significantly with the addition of the dampers that exhibited stable hysteretic behavior and dissipated a large amount of seismic energy.

Representative Figure of the Structure:

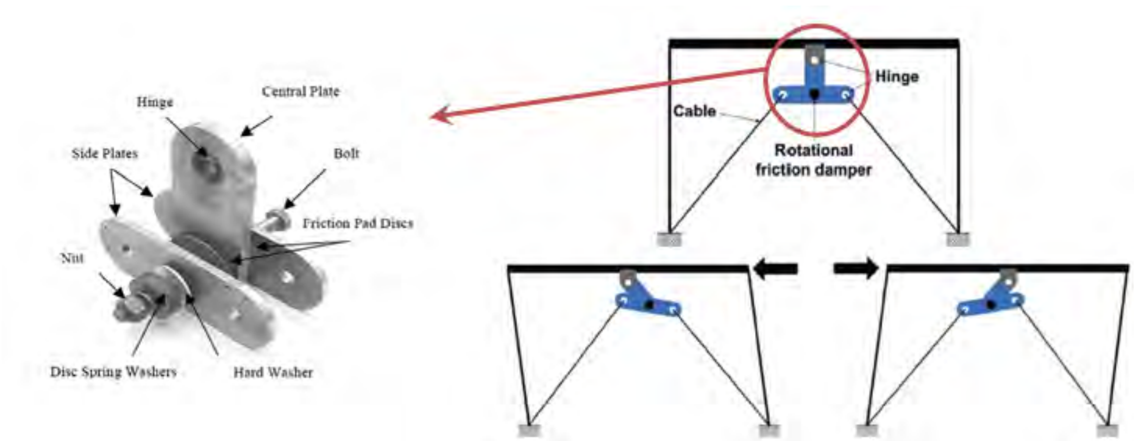


Figure 28 Friction Damper Device [after Kim et al. 2011]

2.20. Karydakis, P, Ioannides G., and Vagias I., 2011

“INSTED -Innovative Stiffness and Energy Dissipation System, Final Report”

Introduction:

The authors presented the principles of the INSTED system for multi-story steel buildings in seismic areas. Vertical composite beams were used instead of the usual moment resisting frames and anti-diagonal bracings with or without eccentricity. In this paper, the system was investigated analytically and experimentally.

System Concept:

The INSTED system was made up from two strong columns of square hollow section and joined together with horizontal beams in a relatively tight arrangement, a vertical vierendeel beam. The vertical strong columns remain elastic with expandable horizontal connections, where plastic hinges are formed and energy dissipation takes place. The horizontal connections can vary in beam section including I-beams, hollow sections, or solid rods and bars. The expandable section was located at the middle of the span in both cases.

The expandable connecting element was moved away from the columns by increasing the length of the replaceable beams that remain elastics, and the developed bending moment was smaller. On the other hand, more plasticity was required due to the bigger relative vertical displacement.

Experimental and Analytical Study, Results and Discussion:

Fifteen tests were performed with three groups of connecting elements: beams of similar section, bars and rods of similar section, and beams of variable connections. The variable sections were designed to maintain structural rigidity until failure during the progressive failure of the system.

In an analytical study, finite element models were used in order to simulate simple bi-linear results without including post-yielding behavior of the steel, final fracture or fatigue. The experimental results were very close to the analytical investigation.

Representative Figure of the Structure:

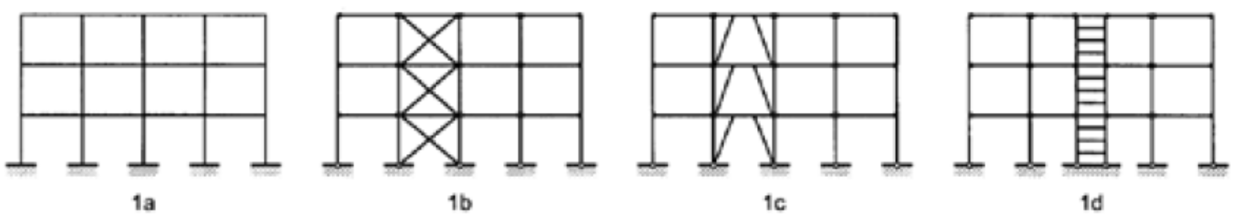


Figure 29 Usual Types of Horizontal Resistance Systems and the Proposed "INSTED" System [after Karydakis et al. 2011]

2.21. Valente, M., Giannuzzi, D., Ballarini, R., and Hucklebridge, A., 2011

"A New Dissipative Bracing System for Steel Structures"

Introduction:

This paper presented a new alternative dissipative bracing system for earthquake-resistant steel buildings, named braced ductile shear panel (BDSP) system. In past, moment resisting and concentrically braced frames were using for earthquake resistant steel buildings. However, moment resisting frames had limited stiffness and concentrically braced frames had limited ductility. This paper included the results of numerical investigations in order to show insufficiencies of moment resisting and concentrically braced frames.

In the first phase of the study analytical models and finite element models merged together. Dimensions, geometry and other parameters were defined in order to make the behavior of the BDSP system as close as possible to the initial concept. In the second phase, the favorable effects of the well-designed BDSP system on steel were evaluated.

System Concept:

The system was composed of four concentric X braces. These I-shaped braces were placed in series with a yielding rectangular ductile shear panel, and transfer the lateral displacements arising from the lateral load on the frame to the shear panel. The ductile shear panel was composed of non-slender in-plane plate elements and boundary flanges. The limiting seismic strength demand on the bracing system was defined by the strength of the ductile shear panel in the series configuration.

Energy dissipation was concentrated only in the shear panel, since only it was designed for plastic strains. Moreover, it could be replaceable by means of bolted connections. Therefore, this system can be used both in new buildings and also as a retrofit.

Analysis, Results and Discussion:

ABAQUS was used in the formation of detailed finite element model in order to predict the behavior of the bracing system taking into account geometric and material nonlinearities. In the numerical models, shell elements were used to represent the braces, the ductile shear panel and the connection elements. Different yield stresses were used for the shear panel and other parts of bracing system. Then, force displacement curves were obtained from fully reversed displacement cycles applied to the top nodes. So, the response of the bracing system under cyclic lateral loading was obtained. From all finite element analysis, it was concluded that plastic strains were localized completely inside the BDSP web.

In the second part of analysis, the force-displacement relationship obtained from the first phase was used to define the properties of nonlinear links used in order to model the bracing system for global analyses.

From the results of the numerical investigations, the proposed bracing system can protect the structural elements of the frame by preventing them from damage under severe seismic action, and energy dissipation mostly concentrated in the device.

Representative Figure of the Structure:

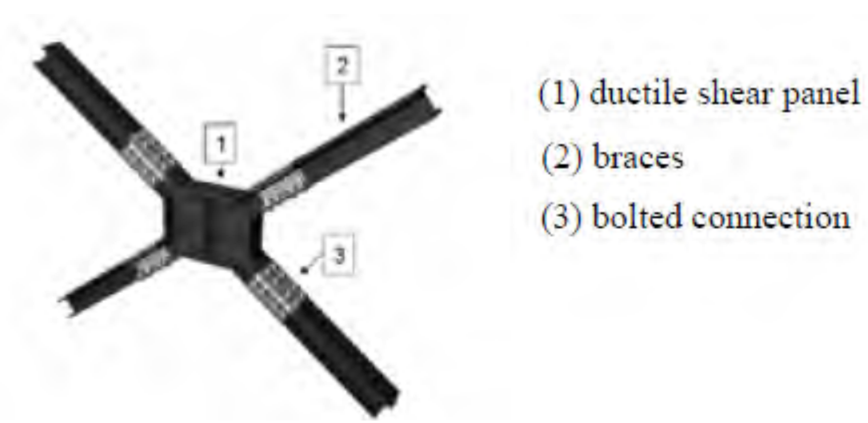


Figure 30 Overview of the Dissipative Bracing System [after Valente et al. 2011]

2.22. Filipov, E., Hajjar, J., Steelman, J., Fahnestock, L., LaFave, J., and Foutch, D. 2011

"Computational Analyses of Quasi-Isolated Bridges with Fusing Bearing Components"

Introduction:

The work presented in this paper is an investigation of prescribed sequential fusing of specific components of bridge systems such that critical components can maintain their integrity after an earthquake. The examined earthquake resisting system is an extension of common bridge design in high seismic regions. The fuse mechanism is implemented at the interface between the substructure and superstructure, which remain elastic. The goal is to study the global bridge system quasi-isolated response when subjected to large seismic motions.

System Concept:

The bridge models were analyzed using the open source, nonlinear seismic analysis program OpenSees. Elements in the bridge superstructure were modeled as linear elastic and the girders were modeled as linear beam-column elements. The deck was modeled using four-node shell elements with linear elastic behavior and low-profile fixed bearings were implemented at one of the intermediate pier, while Type I or Type II elastomeric expansion bearing were used at the other pier and abutments.

Analytical Study:

Using the OpenSees program, a preliminary parametric study using transient nonlinear dynamic analysis was performed. The base bridge model was simulated using a synthetic earthquake record generated for Paducah, KY. A baseline set of analyses were completed using strong ground motions in the transverse direction at different intensities. Initial results show that the bearing friction force has a large influence on the superstructure displacement in the transverse direction. Also, the abutment back wall tends to limit longitudinal displacements.

Representative Figure of the Structure:

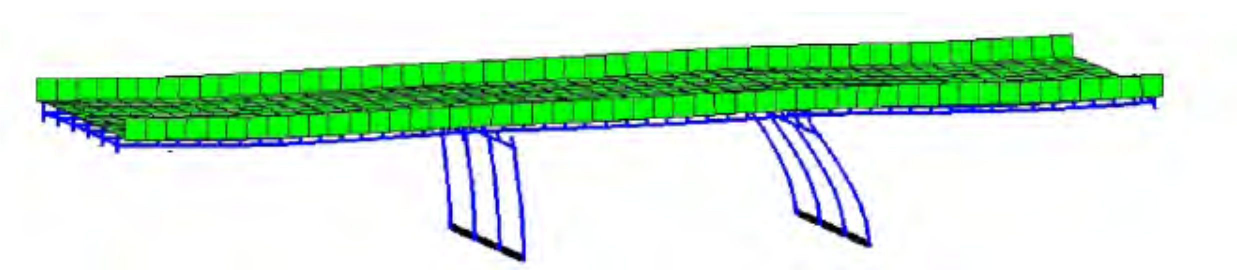


Figure 31 Basic bridge prototype model created using OpenSees [after Filipov et al. 2011]

2.23. Shen, Y., Christopoulos, C., Mansour, N., Tremblay, R., 2011

"Seismic Design and Performance of Steel moment-Resisting Frames with Nonlinear Replaceable Links"

Introduction:

A disadvantage of the current design in MRFs is that they are expected to sustain significant damage to structural members during seismic events. A replaceable link located at expected inelastic yielding locations can provide an alternative to this. An experimental study was conducted to develop and validate the replaceable link concept.

System Concept:

The links are designed with smaller capacities than the beam section. This provides a weakened section, away from the critical welds at the column interface, where a plastic hinge can form. Two link types were examined: W-sections with endplates connections and back-to-back channels with bolted web connections. A 5-story prototype building was design and analyzed for the full scale testing validation.

An advantage of the proposed system is that damaged links after an earthquake can be easily inspected and replaced which minimized disruption time of the structure. Also, this allows for more independent control of beam stiffness and required strength. This provides a more efficient and cost effective structure.

Experimental Study, Results and Discussion:

The experimental test set up represented a typical first floor exterior beam-to-column joint. A column was fabricated with a beam stub for both link type connections and mounted to a strong wall. The loading was implemented through the laterally supported beam. Four full scale tests were conducted under standard cyclic loading.

Results showed that the MRF with nonlinear replaceable links exhibited strength and ductility equivalent to current design procedures. The end-plate links provided greater energy dissipation than the bolted web links, where the bolted web links reached significantly higher rotational capacity. It is noted that additional research is needed to better understand the global behavior of a building assembled with replaceable links.

Representative Figure of Structure:

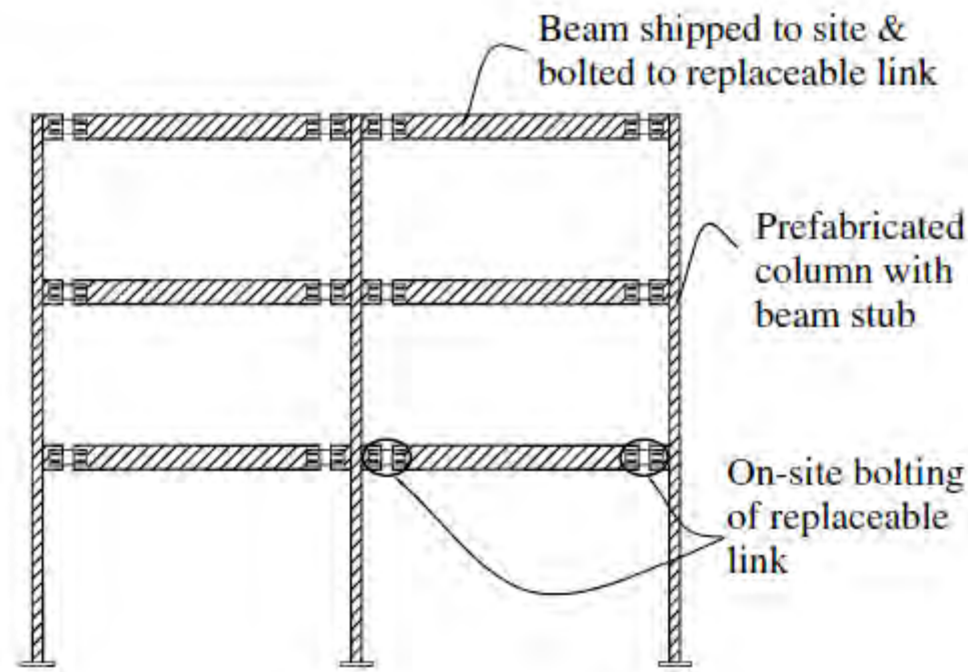


Figure 32 Replaceable link concept [after Shen et al. 2011]

2.24. Mansour, N., Christopoulos, M., Tremblay, R., 2011

"Experimental Validation of Replaceable Shear Links for Eccentrically Braced Steel Frames"

Introduction:

An Eccentrically Braced Frame (EBF) is designed for seismic lateral load resistance. A section of the beam elements within the frame are ductile in behavior in order to dissipate energy. Current design involves implementing the ductile link as part of the floor beam, causing an overdesign of the beam. This drawback is addressed by creating a replaceable yield link which is decoupled from the structural element. The concentrated inelastic deformation in the link can be inspected and replaced following major seismic events.

System Concept:

The research focused on two types of replaceable link configurations. The first is fabricated from a W-section welded to unstiffened end plates. These places are bolted to the floor beam end plates. The second link is an assembly of two channel sections, back-to-back, connected to the floor beam through the web. The connection can be either bolted or welded. The specimens of interested were considered to be at the second floor of a 5-story EBF.

Experimental Study, Results and Discussion:

Link component test were conducted in order to verify that the links were able to achieve a ductility capacity of 0.08 rad plastic link rotation. The specimens were subjected to a constant shear force along their length, equal reverse curvature bending moments at the ends, and no axial force. It was shown that the replaceable links were able to exceed the required ductility capacity.

In order to assess the global performance of the EBF with replaceable links, a second experimental testing program was executed. A test frame representing the first story of a 5-story EBR was assembled with the replaceable link. Lateral load was applied to the floor beam through two actuators reaction onto the strong wall. Cyclic shear deformations were imposed on the frame.

When the test specimens were compared to a bare steel link, it was found that the transfer of shear was 14% greater. It was also noted that the presence of a composite concrete slab did not restrain the link from achieving large shear deformations. Replaceability of the link sections was confirmed, even with residual deformations of 0.5% drift with bolted and welded web connections.

Representative Figure of Structure:

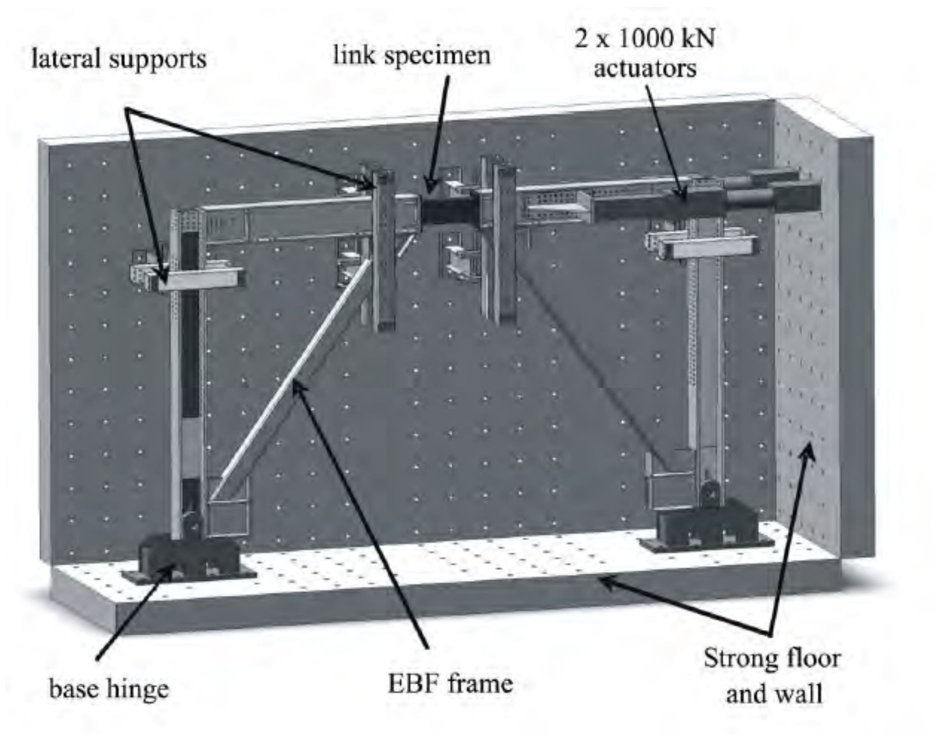


Figure 33 EBF with replaceable shear link test set up [after Mansour et al. 2011]

3. Structures with Self-Centering

3.1. Garlock, M.E.M., Li, J., and Blaisdell, M.L., 2006

"Collector Beam Interaction with Steel Self-Centering Moment Frames"

Introduction:

This paper analytically evaluates the effects of floor diaphragm stiffness, strength, and configuration on the seismic response of a SC-MRF. It is observed that this system exhibits both energy dissipation and self-centering properties. Energy dissipation was provided by supplemental elements that deform due to the gap opening behavior. PT strands were used to provide self-centering.

System Concept:

The system is composed of steel frame with PT strands and energy dissipative angles and bars. The beams in the frames were post-tensioned (PT) by either high strength steel strands or steel bars. This system provided a restoring force to the system that resulted in self-centering. Supplemental elements such as top-and-seat angles, steel bars, or friction devices provide energy dissipation. The beam-to-column connections are characterized by a horizontal gap opening which is closed under earthquake loading. The post-tensioned strands compress the beam flanges against the column flange to resist moment, while the friction at the compressed beam-column interface resists beam shear. Moreover, the angles also resist moment and beam shear while dissipating energy under seismic loading.

Analytical Study, Results and Discussion:

The SC-MRF prototypes were modeled in DRAIN-2DX. The prototype building was a 6-story 6-bay steel frame with 30 foot bay widths and 13 foot story heights. The prototype building was subjected to nonlinear time-history analyses with six ground motions. In this study, the floor diaphragm was represented by collector beams and two different collector beam layouts were evaluated. There were a 3 and 15 collector beam layout. According to analytical results, larger collector beam stiffness showed smaller relative displacements between the SC-MRF and the floor system and larger axial forces, moments, and strains in the SC-MRF beams. Moreover, smaller collector beam strength resulted in more collector beams yielding, which in turn caused smaller roof displacements, story drifts, and relative rotations in addition to larger residual drifts. Finally, using a larger number of collector beams improved performance through added redundancy by reducing the percentage of collector beams that yield in the frame.

Representative Figure of the Structure:

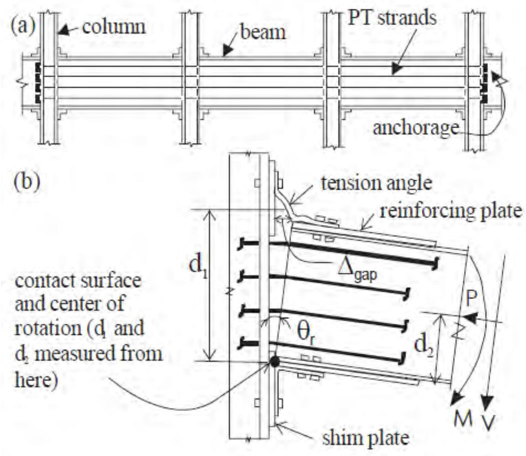


Figure 34 Schematic View of SC-MRF and PT connection [after Garlock et al. 2006]

3.2. Ikenaga, M., 2006

"Self-Centering Column Base Analysis"

Introduction:

In this paper, self-centering column bases are presented to show that reduction occurs in their residual deformation. Self-centering system joints can reduce the residual deformation; however, if column bases sustain large plastic deformation, it is likely that residual deformation will not be suppressed adequately. Therefore, self-centering column bases are developed using a PC bar and steel damper.

System Concept:

Self-centering column bases are composed of a PC bar, steel damper and grade beam. The wide flange steel column is placed on the top of grade beam, with a pair of PC bars connecting the column and beam. The ends of the PC bars were supported by the bottom flange of the grade beam at the bottom and the horizontal stiffener of column at the top. These supporting locations of the column and beam were reinforced by stiffeners. The column base begins to rotate when one flange is decompressed by bending. This causes the system to behave as a pin. Since the damper is attached to the column base the system possesses additional strength, stiffness and energy-dissipating capabilities after decompression.

Analytical Study, Results and Discussion:

A static pushover analysis and dynamic analysis were performed to confirm the theory that energy dissipation and increased stiffness and strength will result from the use of PC bars at the base of columns. The static analysis yielded behavior of the structure that was stable for both positive and negative deformation and several repetitions. The stiffness and moment from the dynamic analysis were similar to those predicted by the static analysis.

Representative Figure of the Structure:

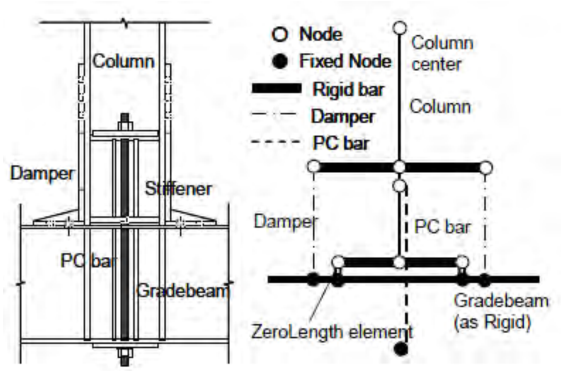


Figure 35 . Self-Centering Column Base [after Ikenaga et al. 2006]

3.3. Walsh, K.Q. and Kurama, Y.C., 2008

"Behavior and Design of Anchorages for Unbonded Post-Tensioning Strands in Seismic Regions"

Introduction:

The authors discuss the results of an experimental study on the behavior and design of anchorages for unbonded PT strands in seismic regions. Single strand/anchorage systems were subjected to monotonic tension loading, considering various design and construction parameters which could affect the performance of a strand inside an anchor.

The primary purpose of this research was to investigate the ultimate strength and strain capacity of different strand configurations while developing guidelines for testing and design. Therefore different strand samples were tested and strand stress and strain data, elapsed time, applied load, crosshead displacement, and strand elongation were recorded.

System Concept:

This structure is composed of unbounded PT tendons, PT anchors, and concrete. High strength PT tendons were used between precast beam column and wall members to provide lateral resistance under seismic loading. The gaps at the joints between structural members govern the lateral displacements of the structure. Use of the unbonded tendons is intended to reduce concrete cracking and delay the yielding of the strand. Moreover, this structure offers self-centering capability through the PT force. These kinds of unbonded PT strands yield a wide variety of applications and could be used in frames, shear walls and coupled walls.

Experimental Study, Results and Discussion:

Cast anchors, barrel anchors, and anchor wedges seven wire strands were tested in this study. The dimensions and properties of the anchors were varied. From test results; the maximum stress and strain capacity of the strands is controlled by the fracture of individual strand wire inside the anchor wedges. Moreover, the strand wire fractures resulted in a reduction in the self-centering capability of the subassembly upon unloading as well as a reduction in the lateral stiffness of the structure during the subsequent loading cycles.

Ongoing Work:

The authors plan to conduct a series of tests with the two ends of the strand specimens embedded in concrete blocks to develop more realistic strand strength. Tests on selected strand/anchorage systems under cyclic tensile loading conditions simulating a seismic event will also take place.

Representative Figure of the Structure:

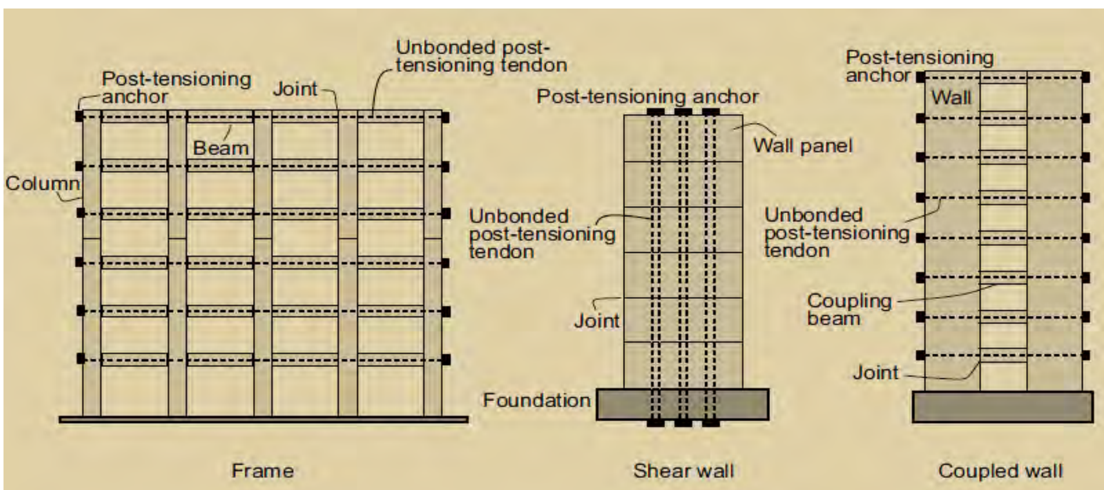


Figure 36 . Applications of Unbounded Post Tensioning Tendons [after Walsh et al. 2008]

3.4. Erkmen, B. and Schultz, A.E., 2009

“Self-Centering Behavior of Unbonded, Post-Tensioned Precast Concrete Shear Walls”

Introduction:

The authors perform an analytical study on the impact of unbounded posttensioning on the self-centering ability of concrete shear walls under cyclic loading. The results are then compared to previous experimental studies.

System Concept:

Tendons are initially pre-stressed vertically in concrete shear walls. When a lateral force is applied and the wall deforms, the pre-stressed tendons apply a restoring force to self-center the structure. The self-weight of the wall and other vertical loads applied also act to return the wall to its original position. Frictional resistance to sliding also assists the wall in re-centering.

Analytical Study, Results and Discussion:

An analytical study was perform on concrete shear walls with varying numbers of tendons and rocking allowed at the base of the wall. It was found that the initial posttensioning force did not have a significant impact on the self-centering capability of the wall, nor does the placement location of the tendons. This indicates that the effect of other loads on the structure can be enough to self-center the walls. Wall panels remained undamaged during the test, and this possibly contributed to the ability to self-center.

Representative Figure of the Structure:

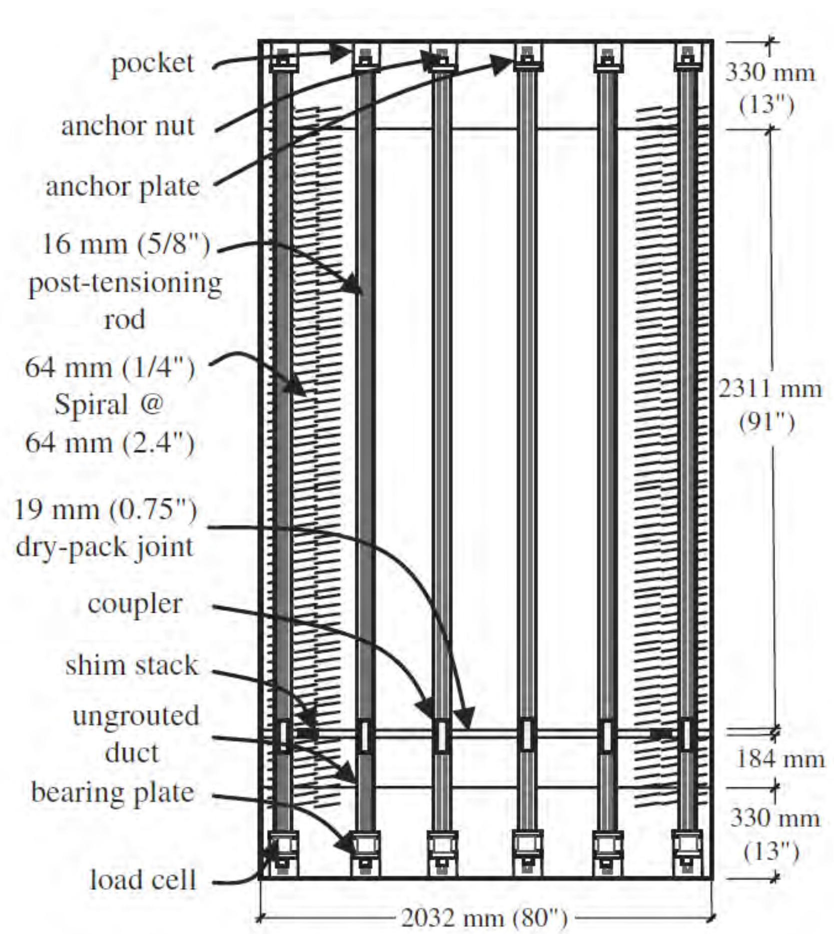


Figure 37 Schematic of a Shear Wall with Vertical Posttensioning [after Erkmen et al. 2009]

3.5. Roke,D., Sause R., Ricles J.M., and Gonner N., 2009

"Damage-Free Seismic-Resistant Self-Centering Steel Concentrically-Braced Frames"

Introduction:

In this paper, analysis results for several SC-CBF configurations are presented. The purposes of SC-CBF are to minimize structural damage under seismic loading and provide significant drift capacity while limiting damage and residual drift. Conventional CBF systems have limited drift capacity before brace buckling and damage leads to deterioration in strength and stiffness. In this paper, system behavior of SC-CBFs is explained, and then the different configurations are considered. Finally, performance based design procedures of the SC-CBF are clarified.

System Concept:

The structure at hand is composed of beams, columns, and braces. Column base details permit the columns to uplift. Gravity loads and PT forces resist column uplift and provide a restoring force after uplift. The beams, columns, and braces are intended to behave elastically under the design earthquake while column uplift controls the force levels in the frame.

The fundamental behavior of the SC-CBF system under a lateral load is rocking on its base. This behavior can be observed when the column under tension from overturning moment decompresses and uplifts from its support. The SC-CBF is designed to decompress at the base at a selected level of lateral loading, initiating a rigid-body rotation (rocking) of the frame. Vertically aligned PT bars were used for SC of the system. They resist the uplift and provided a restoring force to return the SC-CBF to the foundation. The frame members are designed to resist the internal member forces that develop at PT yielding, minimizing structural damage before the PT bar yields.

Analytical Study:

Drift capacity and self-centering behavior of SC-CBF configurations were obtained from the results of a dynamic analysis. Three different configurations were used. The first one (Frame A) was a typical braced frame with PT steel along each column. The second frame (Frame D) consisted of an SC-CBF placed between two additional columns. The third one (Frame D_{DIST}) was a modification of Frame D: vertical struts are added at the upper stories. The seismic responses of several 6-story SC-CBF systems were obtained from nonlinear time-history analyses by using OPENSEES. Beams, columns and braces were modeled as linear elastic and PT steel was modeled using non-linear truss-bar elements. According to the results, frame configuration has an effect on the dynamic response, and ED elements reduce the dynamic drift demand of the structure. Moreover, the first mode response is effectively limited by the rocking behavior; however, the higher modes contribute to the response during rocking of the SC-CBF.

Representative Figure of the Structure:

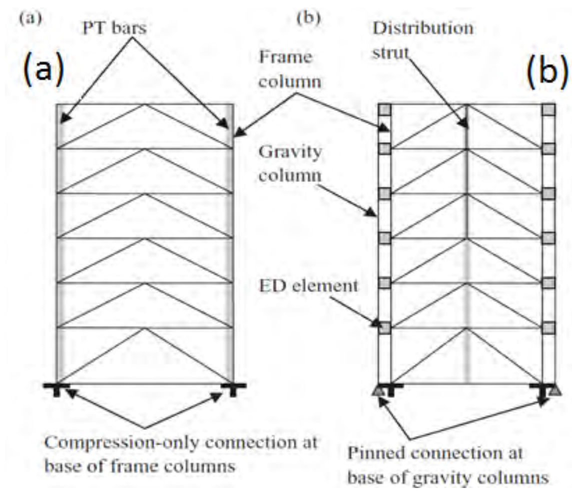


Figure 38 Damage-Free Seismic-Resistant SC-CBF [after Roke et al. 2009]

3.6. Chou, C.-C. and Chen, J.-H., 2009

"Column Restraint in Post-Tensioned Self-Centering Moment Frames"

Introduction:

As an alternative to steel special moment frames, a PT Self-Centering Moment Frame was developed, which uses PT steel to compress steel beams against column. A challenge discovered by previous research was the issue of slab and column restraints. When more than one column is constrained by outer columns, the beam compression force differs from the applied PT force. This paper provides a new analytical technique by evaluating bending stiffness of column and compression forces in the beams based on a deformed column space which matches the gap-opening. The focus of the research is on the restraining effect of columns in a low-rise PT frame. 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.

System Concept:

The analytical method consist of three basic procedures: determine column deformation in accordance with specified lateral displacements at all beam-to-column interfaces along the column height, compute the column bending stiffness at each story by the reaction force divided by the specified lateral displacement, and compute beam shortenings and compressive forces.

The analytical model consisted of a 3-story PT prototype frame, which was required to self-center at both seismic hazard levels of the DBE and the maximum considerable earthquake. Three two-bay PT frames provided lateral load resistance in the east-west direction and were examined in this study. The analytical model was verified using full scale cyclic testing. The experimental model represented the substructure of the three-story frame.

Experimental Study, Results and Discussion:

The experimental set up had three RC columns extending from the foundation to mid height of the second story. Each column was PT to the foundation. A total of 12 PT strands were strung along the beam webs through each of the columns and anchored to the outside columns. Two actuators were positions between the reaction wall and the frame and one actuator was positioned along each beam span. A quasi-static cyclic loading with increasing displacement amplitude was conducted during the experiment.

The research showed that earlier analysis methods using a pin-supported boundary condition at upper story columns represented an upper bound and was overly conservative. It was found that obtaining the column bending stiffness by the deformation of the frame provided more accurate beam compression force estimates. The author concluded the study by noting the proposed analysis procedure based on using deformed shape of columns to assess the restraining effect of columns had been validated through the analytical model and the experimental work, but only followed the first mode predominantly.

Representative Figure of Structure:

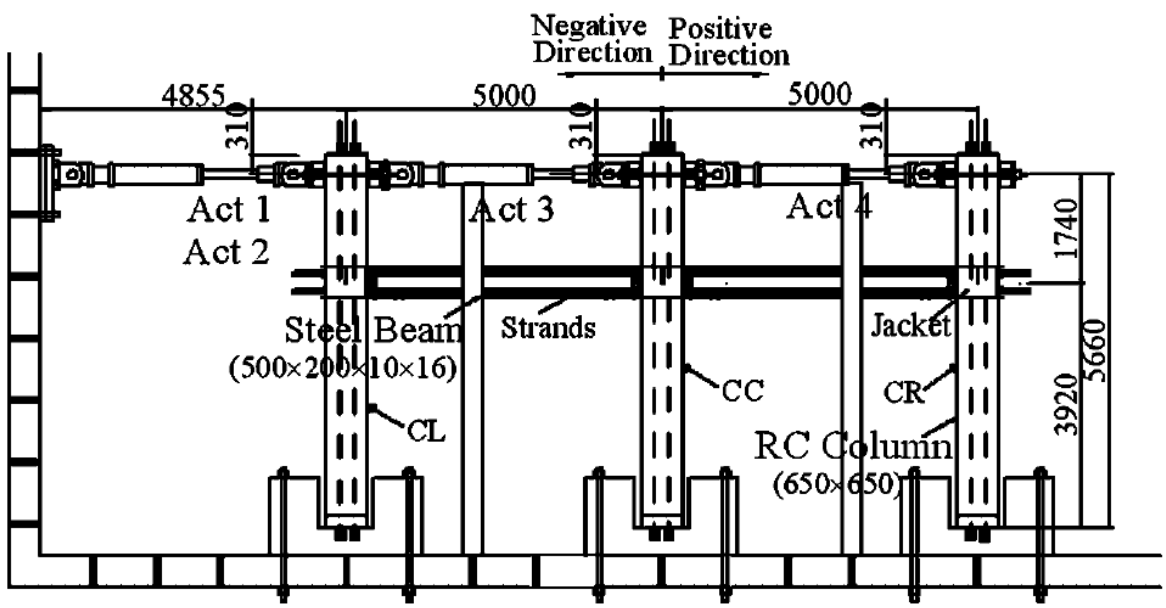


Figure 39 Experimental Test Set Up [after Chou et al. 2009]

3.7. Pampanin, S. 2010

"Damage-Control Self-Centering Structure: From Laboratory Testing to On-Site Applications

Introduction:

In this paper, recent developments and emerging solutions for seismic performance and damage control based on traditional materials and available technology are explained. The purposes of these applications are to create affordable architecturally appealing, high seismic performance structures with limited or negligible damage resulting from earthquakes.

Joint ductile articulated systems, replaceable fuses, floor to lateral load resisting system connections and post tensioned timber buildings are discussed, followed by on-site applications and case studies.

The Joined Ductile Articulated Systems:

The purpose of this system is to concentrate damage in a selected region. In this system, dry joined ductile connections are used to connect the frames and the walls, creating high performance, low damage structural systems. Unbounded post tensioned bars/tendons are used in these joints. Under seismic forces, precast elements are subjected to a controlled rocking mechanism and also provide the structure with a self-centering property. Moreover, the level of damage is reduced by opening and closing an existing gap in these connections. In addition to self-centering and controlling rocking, energy dissipation capabilities are provided by internal mild steel bars. These ductile connections are able to accommodate high inelastic demand without suffering extensive material damage. They can be implemented in a number of structural systems including frames, walls, and dual systems.

The Replaceable Fuses:

Internal mild steel bars or external replaceable dissipaters are used as energy dissipaters. The external fuse system is replaceable and formed by inserting the steel fuse into a steel tube that acts to restrain buckling of the fuse. The external dissipater exhibits very stable flag-shape hysteresis loops. In addition, there is no stiffness degradation due to bond losses when compared to the internally mild steel bars. Either metallic or advanced materials such as SMAs could also be used as an alternative type of energy-dissipating mechanism. The major benefit of the current configuration is replacement and cost effectiveness.

The Articulated Floor System:

This system is composed of standard precast rocking/dissipative frame connections with an articulated or "jointed" floor system. The floor is connected to the lateral beams by slider/shear mechanical connectors. These connectors act as shear keys when the floor moves perpendicular to the beam and as sliders when the floor moves parallel to the beam. As a result, the system is able to accommodate the displacement compatibility demand between floor and frame by creating an articulated or jointed mechanism, effectively decoupled in both directions.

The Pres-Lam System:

This system exhibits high homogeneity and good mechanical properties; therefore, apres-lam system provides high quality resistance to seismic hazards for buildings.

Representative Figure of the Structure:

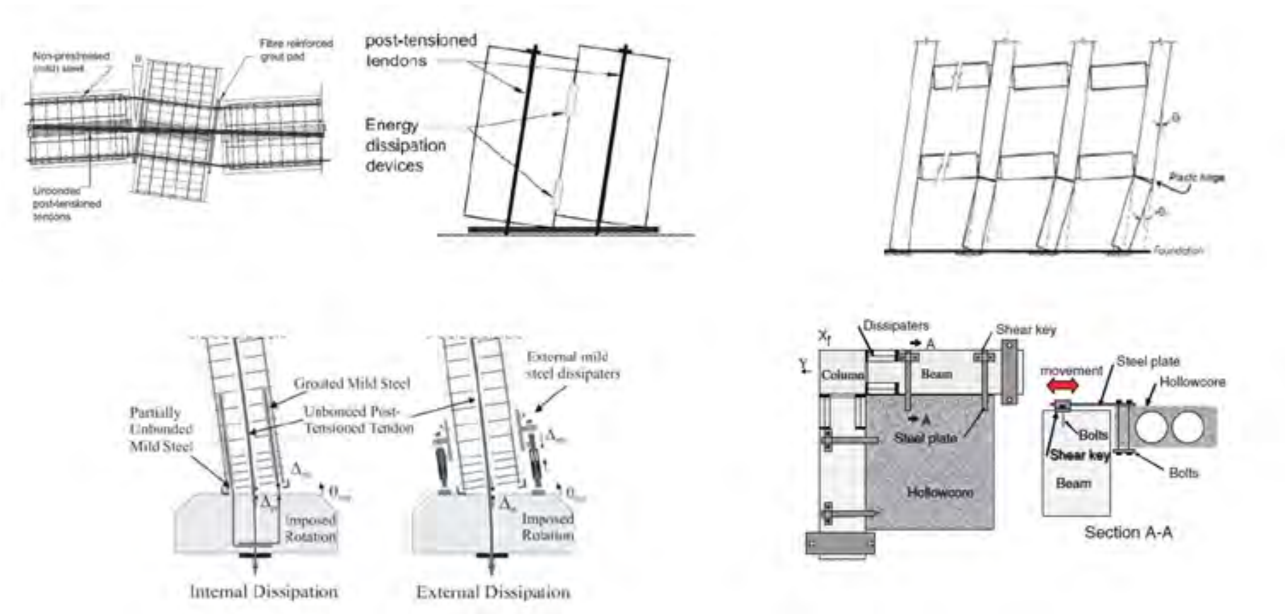


Figure 40 Damage Control Self-Centering Structures [after Pampanin 2010]

4. Structures with Rocking and Energy-Dissipating Fuses

4.1. Hucklebridge, A.A. and Clough R.W., 1977

"Seismic Response of buildings on Soft Foundation Soils"

Introduction:

In this report, the authors explained the effects of allowing column uplift in steel building frames responding to severe seismic loading. In this study, the column uplift effect was observed experimentally and analytically by using 3-story steel frame; and according to the results column uplift reduced seismic loading and ductility demand in the structure when compared with fixed base response.

The report was started with an explanation of overturning effect in seismic response, after that the experimental program was explained in terms of test model, instrumentation and results. Then analytical correlation of test data was observed and the report was concluded with summary and results.

System Concept:

A major earthquake caused lateral inertial forces and resulted in overturning moment at the base of the structure. This overturning moment could easily exceed the overturning resistance provided by the dead weight. Allowing column uplift to the frame created a fuse effect and limited the applied overturning forces on the structure. So, internal forces and the ductility demand on the system were reduced. Moreover, allowing rocking to the system was an economic way to create fuse effect on the system.

Analytical and Experimental Study, Results and Discussion:

Experimental verifications and analytical studies were performed for more effective design application. In addition, experimental data were used in nonlinear analytical techniques in order to show seismically induced overturning effect in a simple structural system.

Three-story, single bay steel moment frame was used for the initial investigation of the uplift phenomenon by performing shake table tests. Uplift response of this system was investigated and compared with the response to similar excitations during which the column bases were securely anchored to the foundation to prevent uplift.

From analytical and experimental studies, it was concluded that the uplift phenomena resulted in a definite reduction in the structural force response quantities. Internal forces were reduced by about one-third through allowing uplift. Moreover, it was realized that, rigid body motions for the single bay frame with pinned column bases led to larger relative story displacements when uplift was allowed.

Representative Figure of the Structure:

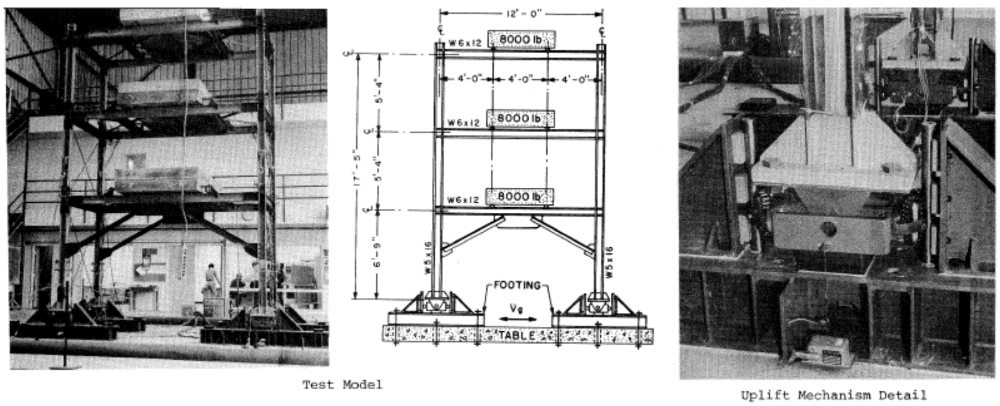


Figure 41 Test Model and Uplift Mechanism [after Huckelbridge et al. 1977]

4.2. Pekcan, G., Mander, J. B., and Chen, S. S., 2000

"Experiments on Steel MRF Building with Supplemental Tendon System"

Introduction:

The authors examine the effectiveness of a supplemental damping system experimentally and analytically. Seven different configurations with various bracing and supplemental damping systems were tested to investigate the effectiveness of each supplemental damping system consisting of ESD and fuse-bars to mitigate the seismic response of steel structures.

System Concept:

The structure consisted of elastomeric spring dampers and fuse-bars. The damper and fuse bar were used to mitigate the seismic response of steel structures. Fuse-bars provide a high initial stiffness and thus limit displacements.

Experimental Study, Results and Discussion:

In this study, ESD devices and fuse-bars were installed in series along with an in-line load cell in a tension-only working tendon system. Fuse bars were fixed at their lower ends to the reaction beam, parallel to the ESD devices. Shake-table tests were conducted with the following configurations: various conventional bracing, tendon-damper, and tendon-fuse plus damper.

According to the test results; ESD devices, with or without a TFD system, reduced the overall seismic response of the structure. Moreover, in tension-only systems, abrupt loading caused high accelerations over the height of the structure. A lack of redundancy in the structure presented further concerns. These disadvantages of tension-only systems can be overcome by pre-stressing the supplemental system with the steel tendon.

<u>*Analytical Study:*</u>

This study also addresses the development and implementation steps of creating a computational model. DRAIN-2DX was used to create a computational model with an iterative solution method. After that, this computational model was then compared with a model implemented in SAP 2000 to check for accuracy in the software methodology.

<u>*Representative Figure of the Structure:*</u>

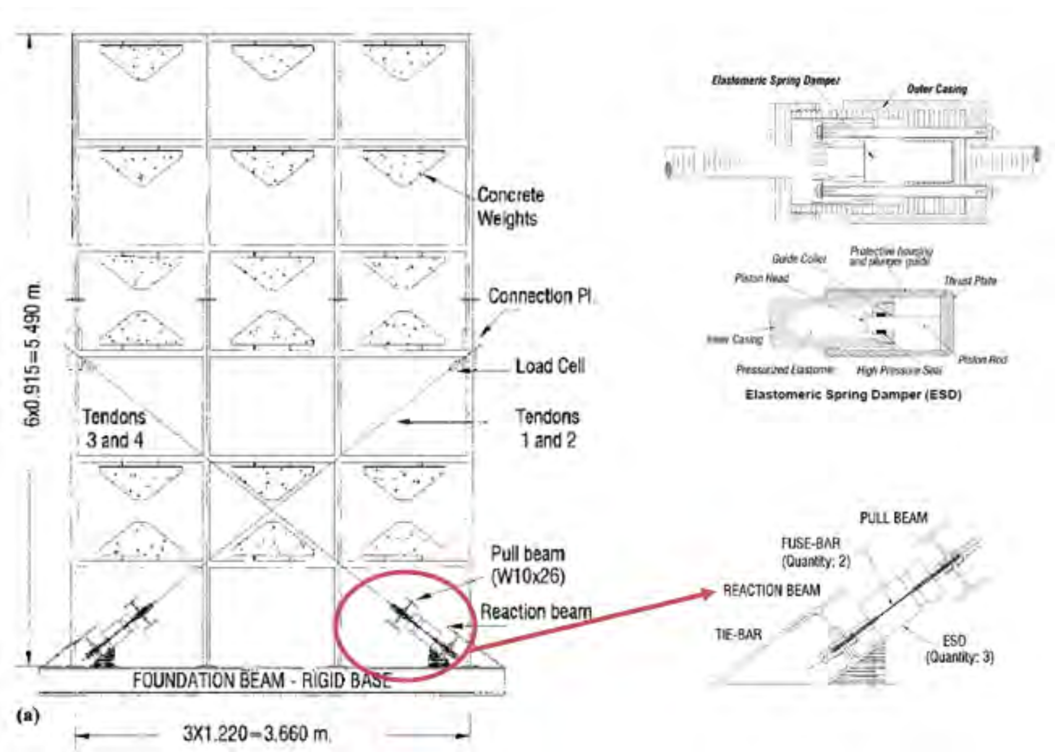


Figure 42 Supplemental Damping System [after Pekcan et al. 2000]

4.3. Ajrab, J.J., Pekcan, G., and Mander, J.B., 2004

"Rocking Wall-Frame Structures with Supplemental Tendon Systems"

<u>*Introduction:*</u>

In this work, the authors propose a rocking shear wall with a supplemental energy-dissipating system of various pre-stressed tendons in different configurations. Tendons are straight, draped, or not included in the model. The sensitivity of the structure to the level of pre-stressing and vertical tendon profile is analyzed. Nonlinear time-history analyses are performed on an analytical 6-story structure using ground motions from El Centro and Pacoima Dam.

System Concept:

The system at hand involves a shear wall that is not rigidly connected to anything at its base, but is free to rock. This system lends itself to large deformation. The general strategy is to take advantage of these large deformations by using elements that can dissipate large amounts of energy from seismic events under large inelastic deformations forced upon them by the rocking of the shear wall. In this case, pre-stressed tendons are used to dissipate seismic energy.

Analytical Study, Results and Discussion:

An analytical study was performed on a 6-story structure with rocking shear walls. The pre-stressing level in the tendons was varied between 0%, 33%, and 67% of the tension yield strength. Tendons were also varied between straight, vertical, and draping.

It was observed that no damage to the structure was induced by the rocking of the system. It was also found that the level of pre-stressing did not have a significant impact on the response of the structure. This is likely because of the overwhelming size of the shear wall in comparison to the tendons. The tendons must still be pre-stressed, however, in order for them to yield and dissipate energy.

Representative Figure of the Structure:

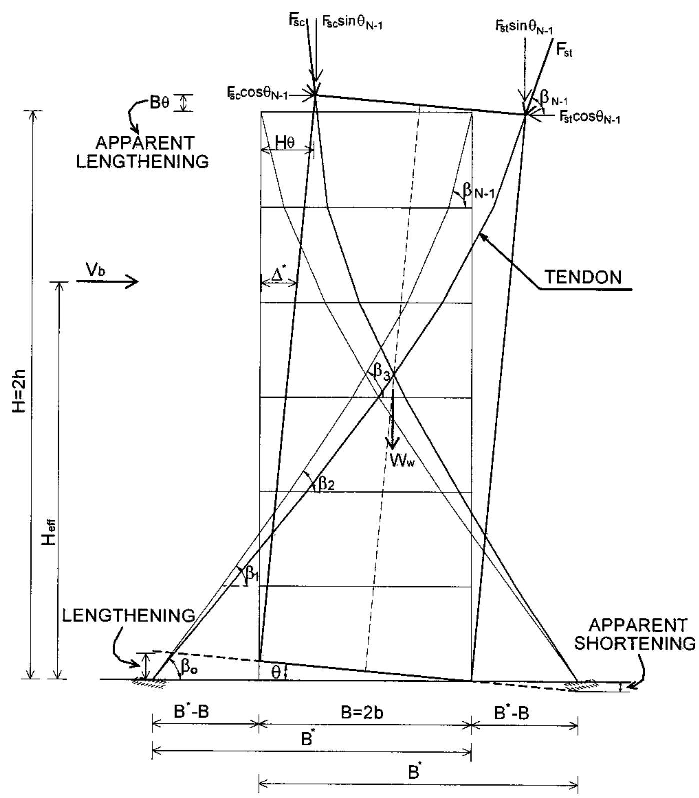


Figure 43 Rocking Shear Wall with Draped Pre-stressed Tendons [after Ajab et al. 2004]

4.4. Ma, Q. T., Wight, G.D., Butterworth, J.W., and Ingham, J. M., 2006

"Assesment of Current Procedure for Predicting the In-Plane Behavior of Controlled Rocking Walls"

Introduction:

This research focuses on the ability to predict dynamic rocking response of PT concrete systems when subjected to earthquake excitations. Three frequently used analytical modeling techniques were compared to shake table test results. Challenges and analysis deficiencies are discussed.

System Concept:

Concrete masonry walls which are allowed to rock about their base are examined. The rocking force due to ground excitation is countered by vertical PT strands. When compared to conventional walls, the system has the ability to soften laterally and rock non-destructively under large seismic events. The PT strands are designed to withstand DBE and still be economically repairable.

Experimental Study, Results and Discussion:

The three frequently used analysis procedures are as follows: Conducting the entire analysis through robust FEM programing, idealizing the wall as a lumped mass system and implementing fiber elements consisting of a series of compression-only springs to model the wall base, or idealizing the wall as a single degree of freedom system, implementing a nonlinearly elastic rotational base connection.

Previous experimental data collected from experimental testing on a PCM wall was compared to the three analysis procedures. The PCM wall was subjected to a scaled 94' Northridge earthquake record through a shake table.

It was found that of the three analysis methods, not one was able to significantly match experimental data in terms of synchronicity and peak displacement. It is concluded that the dynamic behavior of controlled rocking walls is complicated and is not yet accurately modeled based on this procedures. More research is needed in the future.

<u>*Representative Figure of Structure:*</u>

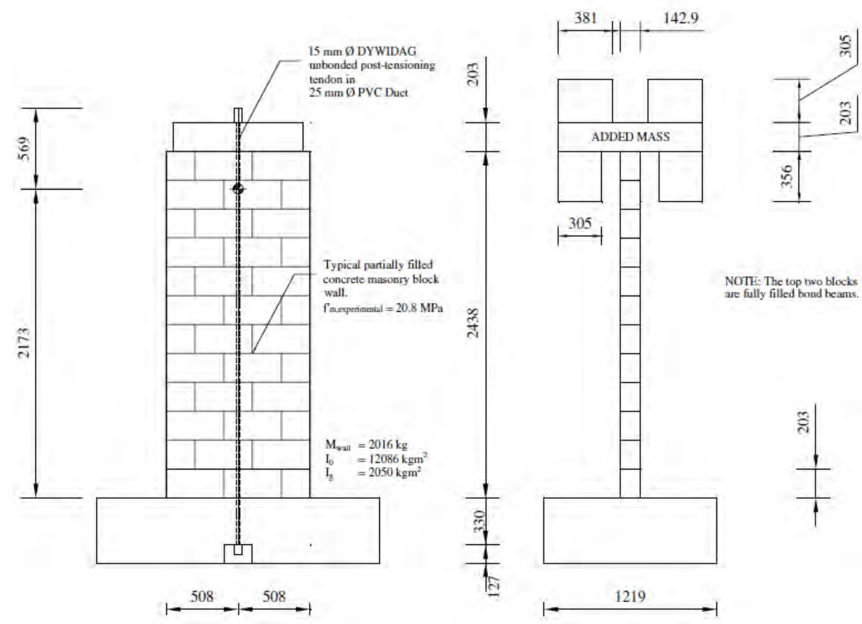


Figure 44 PCM specimen used in shake table testing [after Ma et al. 2006]

4.5. Mahin, S. and Espinoza A., 2006

"Rocking of Bridge Piers Subjected to Multi-Directional Earthquake Loading"

<u>*Introduction:*</u>

In this paper, the authors discuss the bridge pier design which allows rocking. They explained a series of preliminary shake table tests of a simple inverted pendulum reinforced concrete bridge column, conducted for horizontal and vertical components of excitation. The results represented the effects of multi-directional earthquake excitation on the elastic response of bridge columns. Finally, analytical simulations of the elastic rocking response and fixed base response were compared in terms of the benefits of foundation uplift.

<u>*System Concept:*</u>

Rocking behavior can limit local displacement demand and allow the design of smaller footings and members by forming isolation and by reducing displacement and force demands on a bridge.

Bridge structures on a competent soil are generally designed with rectangular spread footings and have fixed base response. This leads to inelastic behavior at or near columns during earthquakes. Although elastic behavior can dissipate input energy, it also results in residual damage to the column. On the other hand, rocking behavior of the bridge pier foundation acts as an isolation mechanism by introducing other modes of nonlinearity and energy dissipation. Moreover, rocking behavior reduces damage in the column and residual displacements in the bridge after an earthquake.

Experimental Study, Results and Discussion:

To model the bridge pier uplift, simple reinforced concrete column and footing resting on neoprene was used. Two and three dimensional excitations were tested. Two recorded earthquake excitations were considered at different amplitude levels or frequency scales in order to examine the behavior of rocking for square footings. The column was expected to remain elastic after the series of test.

In the preliminary tests were performed in order to evaluate the ability of the neoprene pad to mimic soil behavior, evaluate test setup and predict rocking response.

From the experimental results, it was concluded that the periods of the columns and damage levels were different from each other. The period for the fixed base column was 0.28 s and the period for the specimen resting on neoprene pads was 0.52 s. Even though applied excitation level would have damaged a fixed base column, the test column had no damage.

Analytical Study:

OpenSees was used to model the experimental setup. The Beam on Nonlinear Winkler Foundation model was used. After that, analytical and measured displacements were compared. A reasonable correlation was observed between recorded and analytical model.

Representative Figure of the Structure:

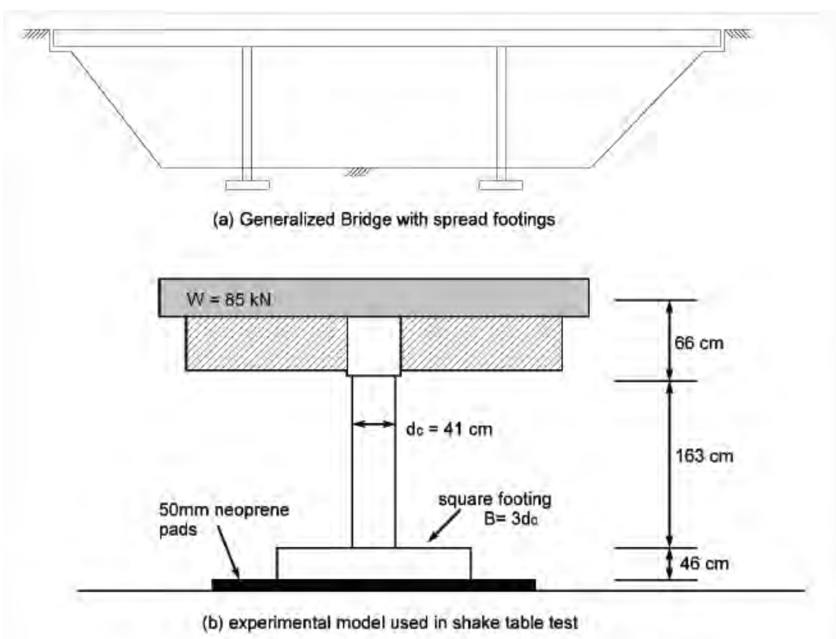


Figure 45 General Bridge Pier and Experimental Test Setup [after Mahin et al. 2006]

4.6. Gajan S. and Kutter B.L., 2008

"Capacity, Settlement, and Energy Dissipation of Shallow Footings Subjected to Rocking"

Introduction:

The authors explained capacity, settlement and energy dissipation of shallow footings subjected to rocking. They showed that the combination of rocking footings with structural base isolation and energy dissipation devices improve the performance of the structure during seismic loading.

System Concept:

The shearing of soil under the footing dissipates energy through friction, and due to uplift related with rocking, shallow footings have significant self-centering characteristics. For load transformation of a frame-shear wall structure supported by shallow foundations, lateral loads during seismic loading are transferred from beams to shear wall to shallow foundation.

Experimental Study, Results and Discussion:

Several series of centrifuge experiments were performed. Each of the tests consists of several shear wall-shallow footing models tested under slow lateral cyclic and dynamic loading conditions. Different types of foundations and loadings were used in the experiments. Slow lateral cyclic loading by an actuator and dynamic base shake were used for shallow foundations.

The results from the tests showed that a rocking footing has a very ductile behavior with negligible loss of capacity, significant energy dissipation capacity, and it also includes self-centering mechanism associated with uplift and gap closure upon unloading.

Representative Figure of the Structure:

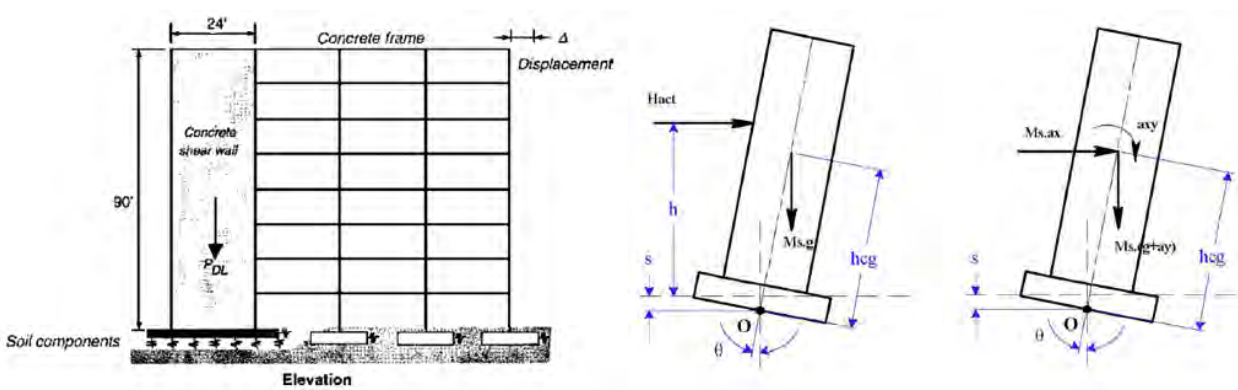


Figure 46 Shear Wall and Frame Structure supported by Shallow Foundations [after Kutter et al. 2008]

4.7. Tremblay, R., Poirier, L.-P., Bouaanani, N., Leclerc, M., Rene, V., Fronteddu, L., and Rivest, S. 2008

"Innovative Viciously Damped Rocking Braced Steel Frames"

Introduction:

A Viscously Damped Controlled Seismic Rocking system is proposed and evaluated. A parametric study was carried out to evaluate the seismic performance of the VDCSR system for 2, 4, and 6-story building applications. Also a design model is created and compared to experimental results.

System Concept:

The VDCSR system is design to enhance the seismic performance and reduce force demand of the building structure. Column uplift and rocking is allowed over the foundation. Embedded dampers or damper mounted beside the columns control the uplift force created by the overturning moments. The system is applicable for new designs and seismic retrofit projects.

Experimental Study, Results and Discussion:

An analytical model was created using SAP200 and used to predict the seismic response of the system. A half-scale model of a 2-story rocking chevron braced steel frame was tested using a multi-cellular shake table. A nonlinear time-history dynamic analysis of both the prototype and model structures was conducted to validate the assumptions made in design of the test model. The test model was subjected to ground motion records based on three locations exhibiting three different seismic settings. These locations included Montreal QC, Vancouver, BC and Los Angeles, CA. The frame was also subjected to harmonic signals with various amplitudes and frequencies.

The analytical testing showed that the system has the potential to reduce column uplift loads compared to conventional braced steel frames. All of the structures were able to sustain design ground motion demand without structural damage at the peak later displacements. Also the viscous damper properties were confirmed through dynamic testing.

Representative Figure of the Structure:

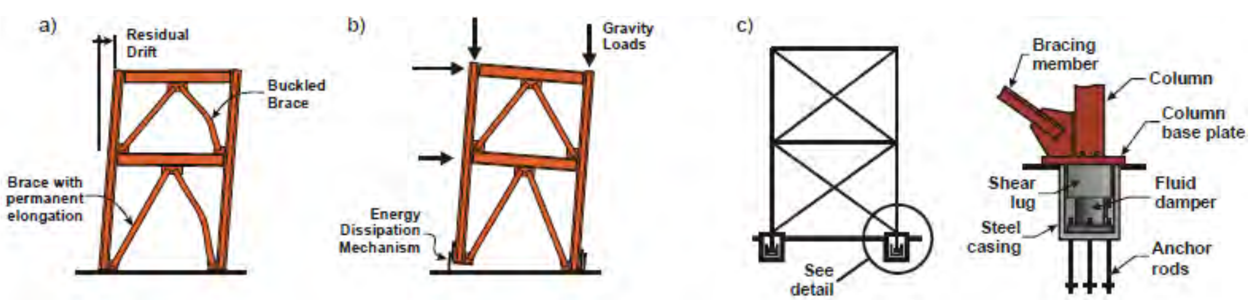


Figure 47 a) Expected seismic damage in concentrically braced steel frames; b) Rocking braced frame; and c) Proposed viscously damped controlled seismic rocking (VDCSR) braced steel frame system

4.8. Nakamura, Y., Saruta, M., Nakanishi, T., Wada, A., Takeuchi, T., Hikone, S., and Takahashi T. 2008, 2009

"Development of the Core-Suspended Isolation System"

Introduction:

The authors explain a CSI system, a new type of structural system. The mechanics of this system are clarified using the results of shake table tests and static loading tests. An overview of the first building using the CSI system is then given.

System Concept:

The core-suspended isolation system is composed of a reinforced concrete core, double layer of inclined rubber bearings and a hat truss. The double layer of inclined rubber bearings seismically isolate the structure and are installed on top of the reinforced concrete core, creating a pendulum isolation mechanism. An office or residential structure can then be suspended from a hat-truss constructed to the seismic isolation mechanism, effectively isolating it from the motion of the core. As a result, the seismic isolation mechanism allows sway and swing motions of the hanging structure, as well as rocking motion of the core.

Experimental Study, Results and Discussion:

A 1/16 scale model 21-story building with the CSI system was tested on a shake table. In order to study the effect of the tilt angle, the shake table tests were conducted at two angles: 1/10 and 1/5. The first and the second mode periods were obtained from sinusoidal sweep tests and eigenvalue analyses. The first mode caused the hung structure to sway, while the second mode resulted in rocking. It was concluded that, based on the maximum amplitude of response for each part of the model, the CSI mechanism significantly isolates the suspended structure.

Static load tests were conducted to investigate the hysteresis characteristics of full-scale rubber bearings under imposed rotational and horizontal displacements. The results of static loading tests of inclined rubber bearings demonstrate that the horizontal stiffness of a rubber bearing slightly decreased with increasing inclination.

Implementation of CSI system:

The first building using the CSI system was constructed in Tokyo, Japan. The seismic isolation mechanism of the 4-story building consists of two layers of four inclined rubber bearings installed at the top of a reinforced concrete core, from which three floors of office structure are suspended by high-strength steel rods.

<u>*Representative Figure of the Structure:*</u>

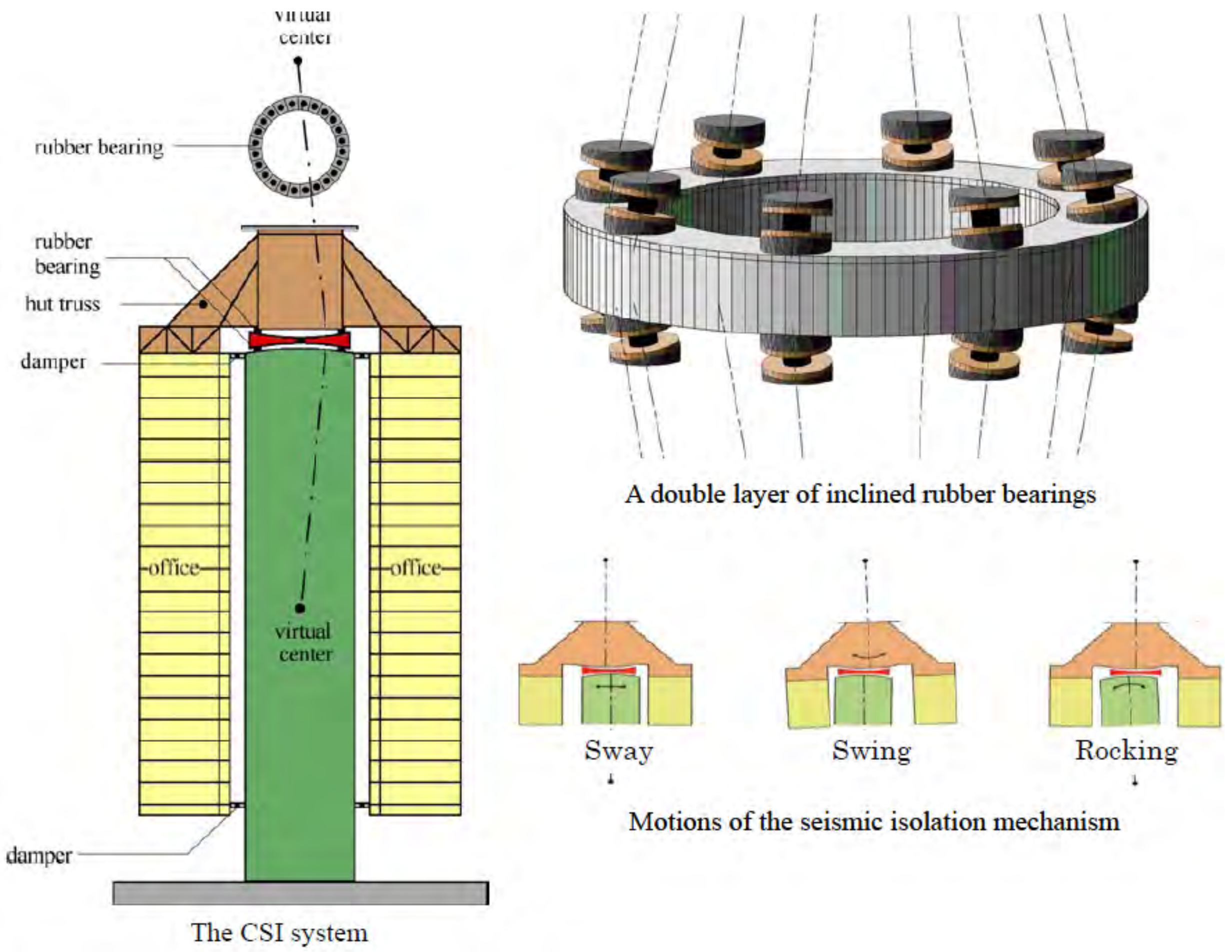


Figure 48 The Core Suspended Isolation System [after Nakamura et al. 2008]

4.9. Midorikawa, M., Ishihara T., Azuhata T., Hori H., Kusakari T., Toyomaki S. and Asari, T., 2008, 2009

"Three-Dimensional Shaking Table Tests on Seismic Response of Reduced-Scale Steel Rocking Frames"

<u>*Introduction:*</u>

The authors examined steel rocking frames with uplift yielding base plates, which allow rocking and uplift under earthquake motions. The four-winged base plates were installed at the bottom of each column at the first story of the rocking frames. In this study, the seismic response of 1/3 scale 3-story steel frames with columns allowed to uplift were evaluated and compared with that of fixed-base frames by three-dimensional shake table testing. Three different input motion conditions from the 1995 JMA Kobe record were used.

System Concept:

The structures in this study were composed of yielding base plates, columns, girders, and bracing members. Base plates act as fuses by yielding due to tension in the columns, and are located at the base of the each column. These plates are composed of 4 wings, and when the base plates yield as a result of column tension during a strong earthquake motion, the columns uplift and allow the building structure to rock.

Experimental Study, Results and Discussion:

1/3 scale, 3-story, 2x1-bay braced test frames were tested on a shake-table for two different base conditions: BPY model and FIX model. In the longitudinal direction, the structure contained two moment-resisting frames with spans of 2 m each. In the transverse direction, the structure contained three braced frames with spans of 2 m.

Horizontal accelerations on the shake table, horizontal accelerations and relative horizontal displacements at each floor level, axial strains of the first story columns and bracing members, and uplift displacements of the first story column bases were measured during the tests. According to the results, when the maximum roof displacements in the BPY model were larger than those in the FIX model in the transverse direction, longitudinal roof displacements were roughly equal or smaller than those in the FIX model. Thus, maximum base shear of the rocking frame was effectively reduced. The axial forces on the columns in the rocking frame were equal or less than those for the fixed base frames, and the response deformation of the rocking frame, excluding the rocking component, was nearly equal to or smaller than the elastic response values of fixed end frames.

Analytical Study:

A modified version of the two-dimensional nonlinear dynamic analysis program DRAIN-2DX was used in the analysis of a 6-story frame with the FIX and BYP models. The details of the modeling and the main assumptions were explained for FIX and BYP models separately. Then, three sets of ground accelerations selected for response analyses were explained.

<u>*Representative Figure of the Structure:*</u>

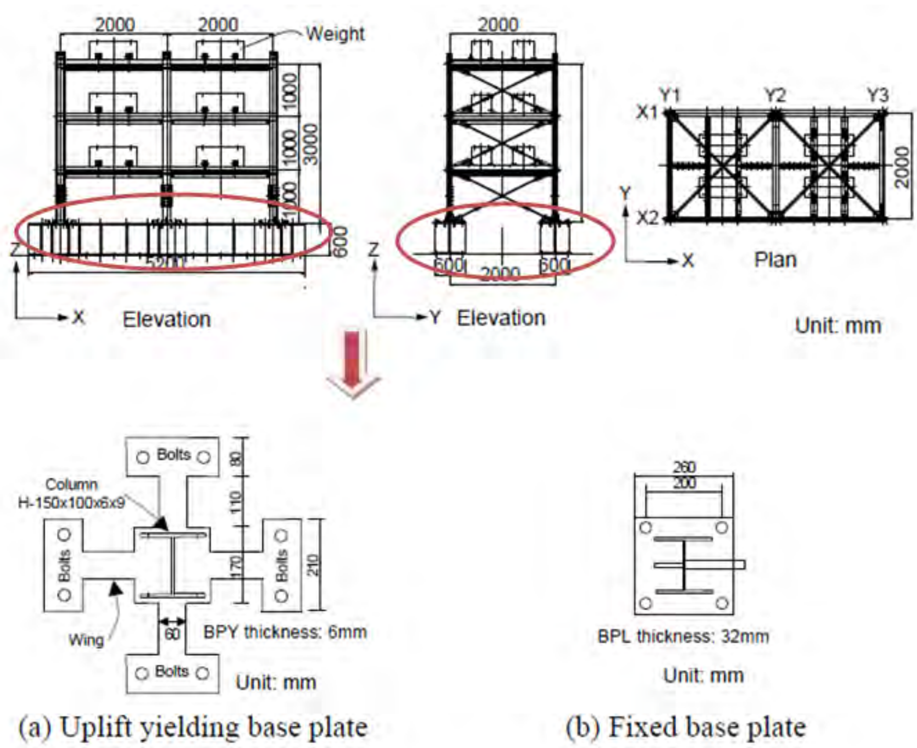


Figure 49 Rocking Frame with Uplift Yielding Base Plate [after Midorikawa et al. 2008]

4.10. Toranzo, L.A., Restrepo J.I., Mander J.B., and Carr A.J., 2009

"Shake-Table Tests of Confined-Masonry Rocking Walls with Supplementary Hysteretic Damping"

<u>*Introduction:*</u>

In this project, the concept of rocking walls was implemented on confined masonry walls. This system was built with low-cost hysteretic EDDs. The main purpose of using confined-masonry rocking walls is to minimize structural damage and residual drifts. This article presented and discussed the results of a shake-table test and the effect of the energy dissipation devices on the dynamic response of the structure was highlighted. First, behavioral mechanisms of rocking walls with supplementary damping were explained. Next, the prototype building and test specimens were described. After providing information about input ground motions, results of experiments were explained in parts.

<u>*System Concept:*</u>

Rocking walls have several advantages and disadvantages. The walls have re-centering mechanisms and a high capacity to sustain large lateral displacements without damage. Unfortunately, they have low energy dissipation capacity, potentially large impact actions and unpredictable seismic response. These negative features are caused by the lack of a reliable source of energy dissipation within the system. EDDs could provide a dependable source of supplementary energy dissipation and decrease the effects caused by impact. Mild steel bars exhibiting a hysteretic response were anchored at the base of the walls to serve as the EDD. This system exhibits large initial stiffness; however, it would be difficult and expensive to replace the system after damage since the EDDs are cast in concrete. The EDDs could be placed at the toes of a rocking wall to dissipate most of the energy through flexure. In this configuration, these devices could also transfer the wall shear force into the foundation, reducing the reliance on friction for shear transfer.

Four EDDs were connected to the base of the wall to be tested. The EDDs transfer forces to the lower corners of the rocking wall; the corners were detailed to transfer these forces to the confining columns. Steel tubes were placed at the base of the confining columns to receive the force from the EDDs by means of pins. The tubes were surrounded by the longitudinal reinforcement of the columns and the base beam. The other end of the EDDs was fully-fixed to the foundation to allow the EDDs to behave like cantilevers. A bracket was attached to the back end of the EDDs. Then the bracket was bolted to the steel plate and anchored to the foundation.

Experimental Study, Results and Discussion:

The shake table tests were performed on a 2/5 scale model of a segment of a prototype 3-story school building. A performance-based design methodology was used in the design of the prototype building system. The design methodology emphasizes four important goals of the structure: prevention of structural damage up to the design earthquake, enforcement of a prescribed mechanism, control of the extent of lateral drift of the structure, and prevention of any residual displacement.

Five historical ground motions were chosen and sixty dynamic tests were run. Several of the tests were used to determine the natural period of structure. The other tests were used to reproduce the seismic demand at different design levels and act as trials to check the instrumentation.

Limited damage and zero residual displacements were observed in any of the tests. The natural period of the structure before propagation was found to be 0.14 s; this lengthened to 0.22 s after propagation. A maximum roof drift ratio was observed as 2.5% without visible damage. Moreover, this system showed the ability to self-center. The tests also validated the expected ability of the EDDs to provide the system with significant supplemental energy dissipation capacity.

Representative Figure of the Structure:

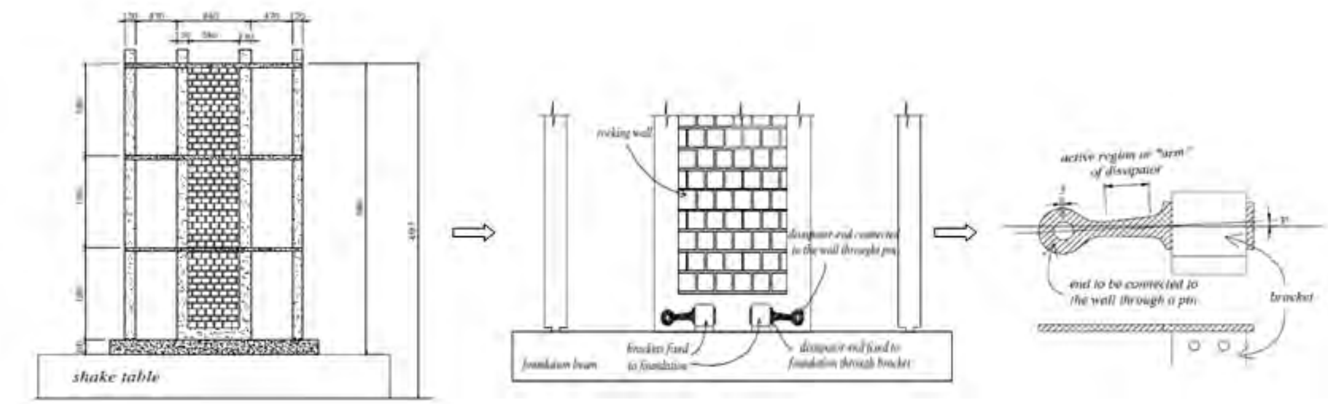


Figure 50 Confined Masonry Rocking Wall with EDD [after Toranzo et al. 2009]

4.11. Liu, W., Hutchinson, T.C., Hakhamaneshi, M., and Kutter, B.L. 2012

"Centrifuge Testing of Systems with Combined Structural Hinging and Rocking Foundations"

Introduction:

Rocking foundation systems have been proven to effectively dissipate seismic energy, but many concerns remain with the overall global behavior in a building system, especially those dynamic interactions with other inelastic and structural components. This paper discusses and compares the seismic response of two extreme structural configurations, structural hinging-dominated systems (SHD) and foundation rocking-dominated systems (FRD). The experimental studies were focused to evaluate the seismic behavior of low-rise frame buildings, considering the yielding mechanisms of fuses and rocking shallow foundations.

System Concept:

The models were set up to represent a moment-resisting frame building founded on a shallow footing. An idealized 2-degree-of-freedom model was developed and used to find the column and foundation stiffness. The fuse yield coefficient and foundation rocking coefficient were defined as principle dimensionless parameters. The SHD system used a rocking coefficient 2.5 times larger than the fuse coefficient, whereas the FRD system used a fuse coefficient 2 times larger than the rocking coefficient. Both the SHD and the FRD system were designed with the same geometric layouts, yet different nonlinear element sizes.

Experimental Study, Results and Discussion:

Analyses using OpenSees, provided a displacement based static pushover response which showed the FRD system had a larger global strength and yield drift ration. The SHD system had lower capacity and yield drift ratio as well as showed similar strain-hardening behavior with conventional frame structures.

Similar sequences of five different ground motions were applied at the bottom of the system with different amplitude and frequency content. It was found the SHD structural fuse observes significant peak transient and permanent deformation demand when excited by moderate and intense earthquake motion. The FRD system greatly reduced the superstructure drift demand due to footing rotation. The fuse element behaved linear elastically with little energy dissipation.

Representative Figure of the Structure:

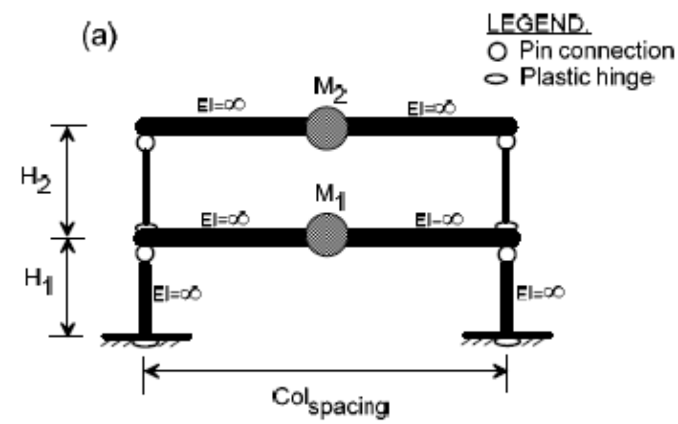


Figure 51 Centrifuge model design: schematic of structural configuration [after Liu et al. 2012]

4.12. Pollino, M., 2012

"Structural and Non-structural Seismic Demands on Controlled Rocking Steel Braced Frame Buildings"

Introduction:

This paper uses the latest publications on controlled rocking steel braced frames to describe and illustrate the transfer of forces through the systems. The demands placed on the non-structural components within each building floor were investigated using a computational model by calculating critical response quantities. Such quantities included inter-story drift, peak floor accelerations and floor spectra. Results were compared with conventional fixed-base ductile brace frame structures.

System Concept:

The controlled rocking brace frame seismic lateral force resisting system consisted of an elastic braced frame within the building. This enabled uplift from the supports prior the yielding and buckling of braces. Along with the tributary vertical weight, the system can be PT for self-centering. The system implemented displacement-based steel yielding devices and velocity dependent viscous dampers are the uplifting location to control the response.

Experimental Study, Results and Discussion:

Using the ANSYS program, the seismic response of the building was calculated by preforming a nonlinear transient seismic analysis. A set of 10 ground motions from Los Angeles DBE were used in the analysis. Frame drift was slightly less than the ASCE 7-10 simplified analysis procedure target drift of 1.5%. A significant floor spectral acceleration was observed at the 2nd mode frequency. Addition cases were run with an increase in element cross-sectional area, which showed significant decreases in floor spectra.

It was concluded that controlled rocking braced frame seismic later force resisting systems can potentially provide increased seismic performance for structural and non-structural components compared to ductile systems and can increase the resiliency and sustainability of a structure subjected to seismic events.

Representative Figure of the Structure:

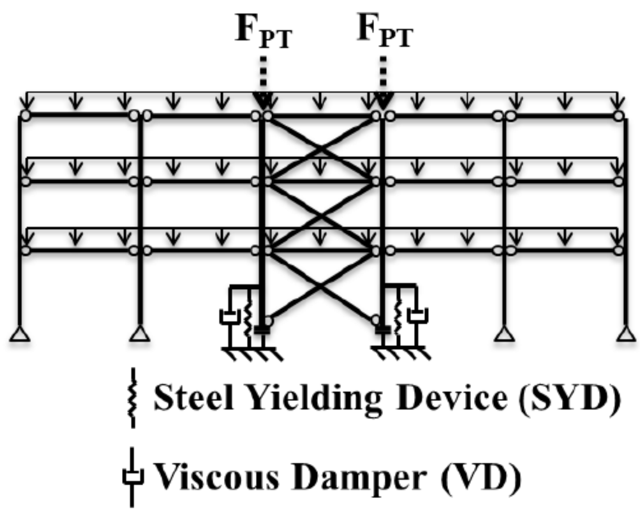


Figure 52 Representative prototype model [after Pollino et al. 2012]

4.13. Saad, A., Sanders, D., Buckle, I. 2012

"Impact of Rocking Foundations on Horizontally Curved Bridge Systems Subjected to Seismic Loading"

Introduction:

In this paper, the seismic performances of curved bridges with controlled rocking foundations are evaluated. Using documented analytical and experimental studies of buildings subjected to controlled rocking, the concept was applied to a three-span curved bridge which is supported on two single column bents and two end abutments. The purpose of the experiment was to compare distribution of the demands on a superstructure and the overall displacement to systems without rocking.

System Concept:

Using SAP 2000, five bridges were modeled in the parametric study. Weight and length of each model was held constant, while the horizontal curvature varied. Each model consisted of three spans with two single column bents. Frame elements were used in modeling the bridge superstructure rather than a finite element model to reduce time-history analyses computation time. The effects of rocking were analyzed by varying the foot sizes.

A gap link element with zero gap was used to models the soil beneath and around the footing. This element contained a lumped stiffness of the soil in compression and free in tension, which allowed uplift of the footing. A nonlinear time-history analyses based on the Northbridge Earthquake record was used for experiment input motion.

<u>*Experimental Study, Results and Discussion:*</u>

Using the Northbridge Earthquake record, preliminary results suggested smaller footing sizes had increased footing uplift versus larger ones, with resulted in less damage to the columns. It was also found the amount of energy dissipation decreased with footing size, while overall bridge displacement increased. This indicated that both column and overall bridge performance are affected by the rocking behavior.

<u>*Representative Figure of the Structure:*</u>

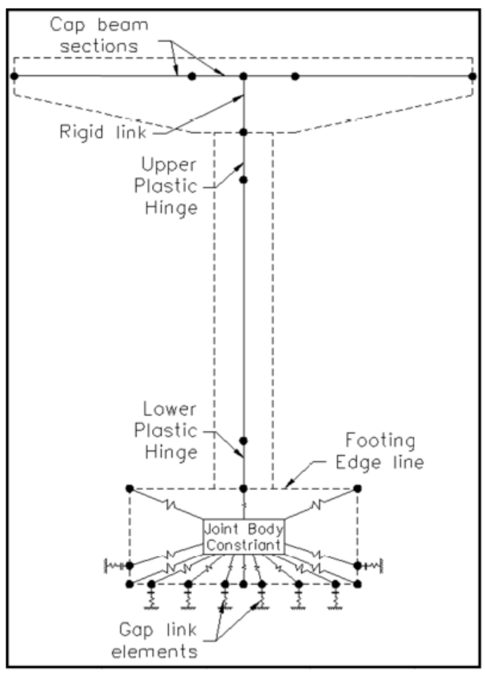


Figure 53 Modeling of the bent element [after Saad et al. 2012]

5. Structures with Self-Centering and Energy-Dissipating Fuses

5.1. Shutt, C.A., 1997

"Hybrid Precast Frame Meets Seismic Challenges"

Introduction:

In this paper, the application of a hybrid precast moment resisting frame is explained. Mild steel and PT strands that can absorb energy and provide self-centering were used in the connections of precast members. Firstly, the mechanism of connections and installation steps were explained, and then the advantage and the applications of this structure were mentioned.

System Concept:

This system is composed of a precast concrete moment frame and PT strands at the connections. This frame is intended to absorb seismic energy independent from the structural members. The post elastic performance of the system is reliant on the connection rather than structural members. Hybrid frame classification is dependent on the connections between the precast columns and the beams. Standard reinforcing and high strength post tensioning steel cables are used in the beams. This combination provided two separate functions to the system: energy absorption and strength. Inelastic behavior from the movement of the joints enables energy absorption. High-strength post tensioned steel gives the joints the strength to resist applied dead, live and seismic loads. Moreover, mild steel at the connections serve as energy dissipaters. Strength and energy absorption are thusly separated from one another.

The elasticity of the joint allows it to open and close to accommodate seismic ground motion. By keeping the initial post tensioning force low relative to the strand's ultimate strength, the high strength steel does not yield. This provides large reserve capacity for deformation.

Installation of the System:

The columns are erected first and equipped with temporary steel corbels. Then the beams were set on the corbels and the reinforcing bars are placed in the trough. Next, the bars are passed through the ducts in the solid ends of the beam. Ducts from beams and columns line up with each other. The gaps between beams and the columns are then filled with a fiber-reinforced grout.

Results and Discussion:

The hybrid precast moment resisting frame offers several advantages over other seismic systems. Some of them are lifecycle costs, simplicity, speed and safety. This system could be constructed economically with higher performance. Moreover, its drift capacity could exceed six percent. When used in this experiment, negligible cracks were observed only at upper stories, and they closed when loads were removed.

Representative Figure of the Structure:

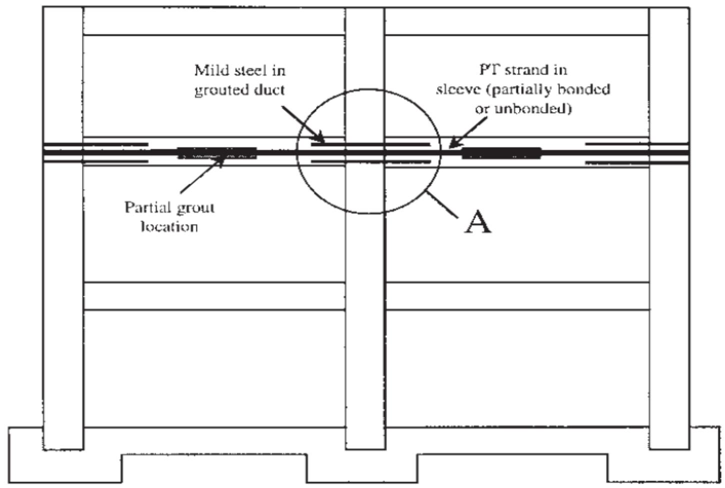


Figure 54 The Hybrid Precast Moment Resisting Frame [after Shutt et al. 1997]

5.2. Kurama, Y.C. and Shen Q., 2000

"Lateral Load Behavior of Unbonded Post-Tensioned Hybrid Coupled Walls"

Introduction:

The authors use an analytical study to assess the seismic behavior and design of unbonded post tensioned hybrid coupled walls. Concrete walls are coupled using steel beams and unbonded post-tensioning, without embedding the beams into the walls, and then subjected to monotonic and cyclic loading. The objective was developing a type of hybrid coupled wall system using unbounded post-tensioning, without embedding the beams into the walls. It was expected the lateral stiffness and ultimate strength of unbonded post-tensioned hybrid coupled walls would be similar to walls with embedded steel coupling beams. Moreover, in the design, the system is intended to soften and undergo large nonlinear rotations without significant permanent residual rotations in the beams or walls.

In the paper, behavior of unbonded post tensioned coupling beams under monotonic loading and cyclic loading were presented. After that, beam rotation behavior was explained.

System Concept:

PT strands and angles were used in the connections of concrete beams to walls. The post-tensioning force was provided by multi-strand tendons. These were placed on both sides of the beam web without contacting the beam. In order to prevent bond between the PT steel and the concrete inside the wall, PT steel was placed into the oversize ducts. By this method, the post-tensioned steel is anchored to the coupled wall system only at the two end locations. The beam-to-wall connection regions included top and bottom seat angles bolted to the beam flanges and to steel plates embedded inside the walls. The purpose of these angles is to yield and provide energy dissipation during an earthquake. These yielding angles could be replaced after the earthquake. Yielding is a desired behavior for the angles when a gap forms between the beam and wall. This gap allows the beam to undergo large nonlinear rotations with little permanent residual rotations. As the walls displace laterally, the tensile forces in the post-tensioned steel increase and resist opening of the gap. Upon unloading, the post-tensioning steel provides a restoring force that tends to close the gaps.

Analytical Study:

An analytical model was developed to investigate the behavior of unbonded post tensioned hybrid coupled walls under seismic loads and to conduct nonlinear static and nonlinear dynamic time-history analyses of multi-story unbonded post-tensioned hybrid coupled walls. The DRAIN-2DX Program was used for the analytical study. In this part of the paper, the modeling approach for beams, walls and the connections were explained. After that, behavior of the unbonded post tensioned coupling beams under monotonic loading and cyclic loading were presented. Moment rotation behavior of the beam and the effect of the gap opening on the stiffness of the beam were explained. According to analytical results, the unbonded post-tensioned steel coupling beams with stiffness and ultimate strength similar to embedded steel coupling beams can be designed to soften and undergo large nonlinear rotations of up to 7.5 percent without significant permanent residual rotations upon unloading.

Representative Figure of the Structure:

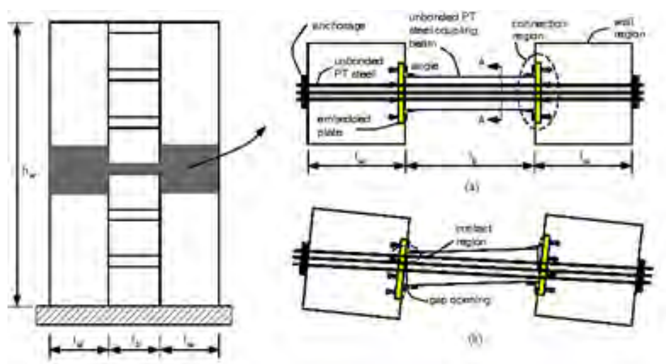


Figure 55 Unbonded PT Hybrid Coupled Wall Subassemblage [after Kurama et al. 2000]

5.3. Filiatrault, A., Trembley, R., Kar, R., 2000

"Performance Evaluation of Friction Spring Seismic Damper"

Introduction:

The evolving concept of the use of passive energy dissipators in seismic design is discussed in this paper. In particular, a self-centering friction mechanism is analyzed numerically and evaluated experimentally. Characterization component test are conducted along with half scale shake table testing in order to assess the seismic performance of the damper system.

System Concept:

The seismic damper consists of a ring spring, or a friction spring, as the dominant energy dissipator. The assembly consists of outer and inner rings. As the damper is axially loaded, the rings begin to slide on the conical friction surface. The outer ring is put into circumferential tension and the inner right experiences compression force. Characterization test of the damper exhibited force-displacement hysteresis loops which were self-centering, repeatable, stable, identical in tension-compression, and identically at almost all frequencies considered.

Experimental Study, Results and Discussion:

Shake table test were performed on a half scale specimen representing a single-story MRF. Lateral load resistance was provided by rigid connections between the floor beam and the columns as well as a bracing member. Tests were conducted for the specimen with and without the damper retrofit. The prototype model was subjected to a push over analysis and four different seismic simulations of the 1940 El Centro earthquake record.

The friction spring damper provided effective reduction of lateral displacement and acceleration levels. Hysteresis loops, resembling those found in the characteristic tests, were also found in the shake table tests proving the self-centering and energy dissipation concepts. The energy dissipation in all tests were found to be sufficient to protect the structure from undergoing severe inelastic deformations.

Representative Figure of Structure:

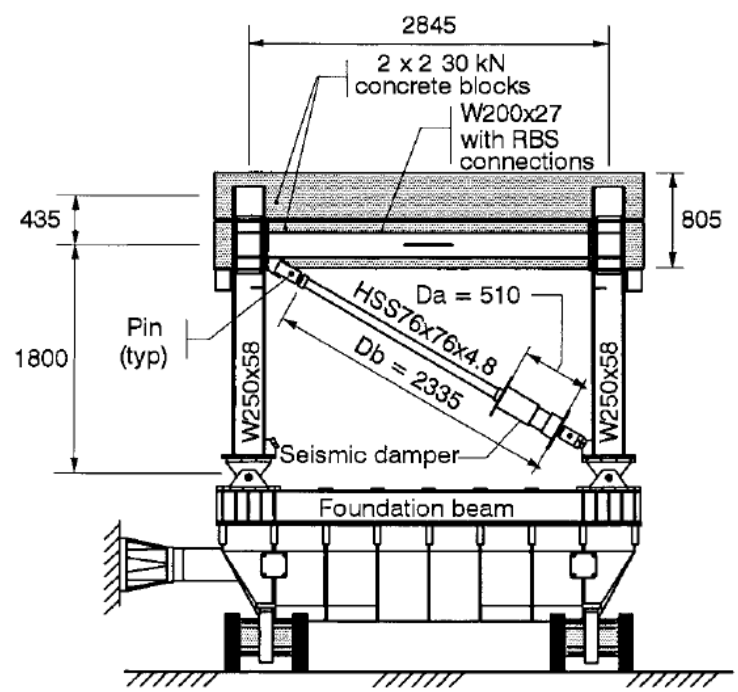


Figure 56 Test structure incorporating seismic damper [after Filiatrault et al. 2000]

5.4. Christopoulos, C., Filiatrault, A., Uang, C., and Folz, B., 2002

"Posttensioned Energy-dissipating Connections for Moment-Resisting Steel Frames"

Introduction:

The authors evaluate the seismic performance of a post-tensioned energy-dissipating (PTED) connection for steel frames experimentally and analytically. High strength post-tensioned bars and energy-dissipating bars are used at connections in an attempt to provide for a ductile connection and avoid some of the fracture stiffness of welded connections, while providing self-centering capabilities for the system. Non-linear time-history dynamic analysis was performed on the analytical model. Component testing was performed on the energy-dissipating bars, as well as a test of a beam to column connection.

System Concept:

This connection type is meant to dissipate energy through energy-dissipating bars and self-center through post-tensioning. Energy-dissipating bars are inserted into steel cylinders to prevent buckling, and attached to the beams and columns of the frame through welded couplers. When the beam rotates, the energy-dissipating bars deform inelastically in compression or tension, providing a mechanism for dissipating energy. Post-tensioned bars through the beam and connected to each column then self-center the structure.

Experimental Study, Results and Discussion:

Component testing was conducted on the energy-dissipating bars with the goals in mind to assess the tension-compression cycles of the bar, to ensure that welded couplers were sufficient to develop the full axial strength of the bars, and to see if the confinement cylinders could prevent buckling of the energy-dissipating bars. A cyclic test was also performed on a beam to column connection for an inter-story drift of 5%.

It was found that the energy-dissipating bars were able to yield in axial tension and compression, and that they effectively dissipated energy. The post-tensioning was then able to self-center the structure. Large deformations were achieved without damaging the rest of the frame.

Analytical Study:

An analytical study was undertaken to develop the relationship between moment and rotation of the PTED connection. The developed model was able to accurately predict the behavior of the connection and outlined procedures for designing post-tensioning and energy-dissipating bars for the PTED.

Representative Figure of the Structure:

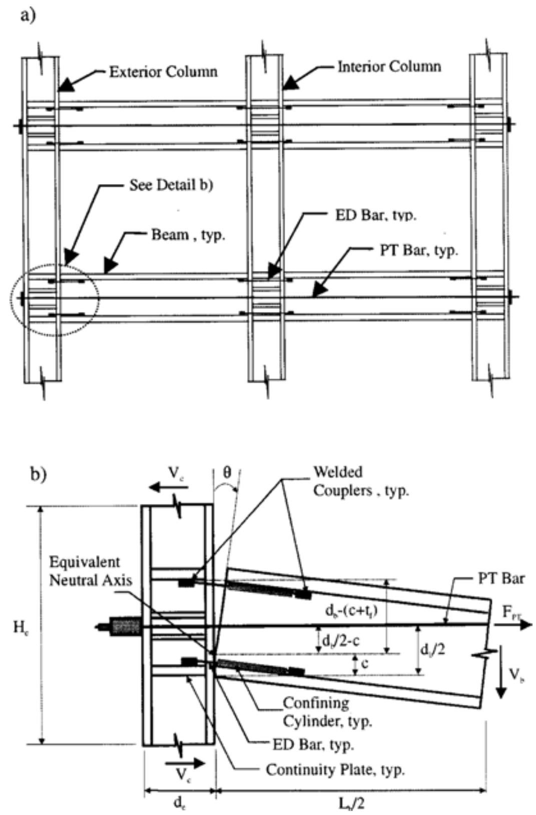


Figure 57 (a) Steel Frame with PTED Connection, (b) Geometric Configuration of PTED Connection [after Christopoulos et al. 2002]

5.5. Pekcan, G., Mander, J., and Chen, S.S., 2002

"Seismic Retrofit of Steel Deck-Truss Bridges with Supplemental Tendon Systems"

Introduction:

The authors investigated tension only brace configurations for steel deck-truss bridges with dampers and sacrificial fuse bars. A one third scale model is tested on a shake table with various configurations.

System Concept:

Tendon elements provide diagonal bracing for steel deck-truss bridges when the bridge is deformed laterally. This can often result in excessive residual drifts after seismic events. Spring dampers or fuse bars are intended to provide a restoring force so that the deck can self-center after a load is applied. The fuse bars are intended to dissipate energy by yielding and deforming inelastically. The goal in mind is to reduce the force that is transmitted to the piers by dissipating some of the energy through the deformation of the fuse bars.

Experimental Study, Results and Discussion:

Tests were performed on a shake table for ten pre-stressed tendon only structures, ten pre-stressed tendons with dampers, and twenty-seven structures with pre-stressed tendons, dampers, and sacrificial fuse bars. The size of the fuse bars was a variable of interest, and had a strong correlation with the magnitude of measured deck displacement, base shear, and bearing shear. Pre-stressing levels were also varied.

It was found that the most desirable configuration included dampers with sacrificial fuse bars. The fuse bars effectively dissipate energy and reduce the magnitude of the forces transmitted to the piers. This is an especially positive result since the fuse bars are easily replaceable after they sustain damage, and thus limit the time that a bridge with this system would need to be closed after an event.

Representative Figure of the Structure:

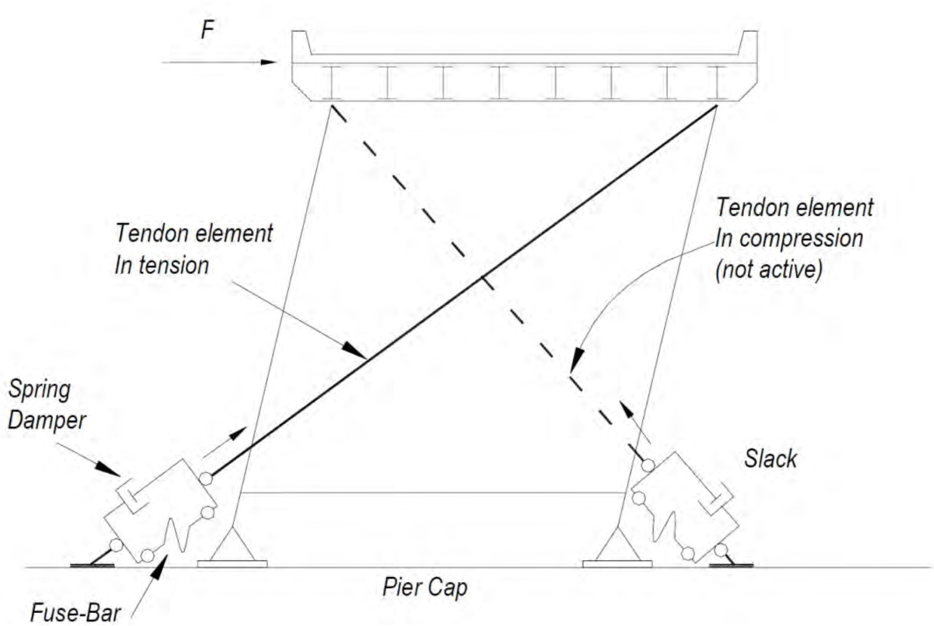


Figure 58 Representation of Tendons with Spring Damper and Sacrificial Fuse Bar [after Pekcan et al. 2002]

5.6. Clifton G. C., Butterworth J., and Zaki R. J., 2003

"Two New Semi-Rigid Joints for Moment-Resisting Steel Frames"

Introduction:

In this paper, two joints (FBJ and SHJ) have been developed and tested to determine their respective behaviors during a seismic event. FBJs are simple to fabricate and erect, and are intended for low levels of design ductility demand. SHJs are also simple to fabricate, but are more complex to erect. They are intended for higher levels of design ductility demand. Both joints can undergo rotation during a severe earthquake while suffering minimal structural damage. Research results show that both of these joints remain effectively rigid up to the design level ultimate limit state earthquake forces because they have been designed and detailed to withstand the expected inelastic rotation associated with the design loads.

System Concept:

The authors tested structures composed of steel frames with FBJ or SHJ connections. Fuses were placed at the connections of the steel frames. The FBJ involves connecting the beam to the column through plates to the top and bottom flanges of the beam, and a plate to the beam web. The SHJ involves pinning the beam relative to the column at the beam top flange level via top flange bolts and a top flange plate. These bolted connections can be replaced. Due to the mechanism of the connections, a dynamic self-centering characteristic is provided.

Experimental Study, Results and Discussion:

Large and small scale experimental tests were undertaken to assess and improve the behavior of the joints at hand. Large-scale experimental tests helped determine adequate bolt size and layout. Small scale tests were performed to determine bolt size, ratios of design shear capacity of bolt group to plate axial strength, the effect of repeated loading on bolts and plates, and the effect of loading rate. Both these semi-rigid joints offer considerable advantages over traditional rigid jointed MRSFs and have the potential to set the future direction for MRSF seismic-resisting system application.

Analytical Study:

Numerical integration time-history (NITH) analyses were undertaken to determine the demands on the system. The computer program RUAUMOKO was used for these analyses. Rotation demands of the joints were obtained from the analytical studies.

Representative Figure of the Structure:

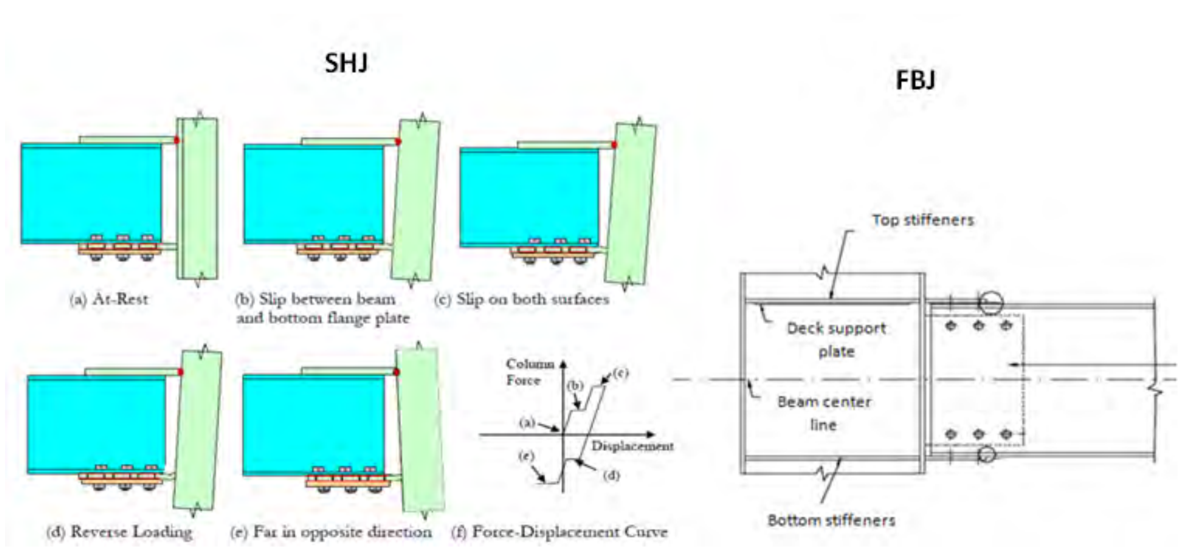


Figure 59 SHJ and FBJ Types of Joints [after Clifton et al. 2003]

5.7. Dolce, M., Cardone D., Marnetto R., Mucciarelli M., Nigro D., Ponzo F.C. and Santarsiero, G., 2004

"Experimental Static and Dynamic Response of a Real R/C Frame Upgraded with SMA Re-Centering and Dissipating Braces"

Introduction:

In most seismic regions, buildings have very low resistance capabilities. Many RC framed buildings in seismic areas were designed with no seismic criteria, considering only gravity loads. One approach to this problem is applying passive control mechanisms to existing structures. In this paper, a new technique to seismically upgrade a RC frame with SMA re-centering and dissipating braces is evaluated. Analyses of the experimental outcomes, including seismic measurements, are presented.

System Concept:

The upgraded structural system consists of four special braces with SMA and NiTi properties increase energy dissipation of the braces. The SMA and NiTi wires are used in their austenite phase so as to exhibit superelastic characteristics and fatigue resistance fat large deformations. The SMA based devices transform any deformation of the brace through tensile deformation of the SMA wires. Wires are pre-stressed to give the brace a high initial stiffness. The tangent stiffness of the device depends on the stiffness of the SMA wire group when an external force becomes greater than the pre-stress force. This wire arrangement yields nonlinear behavior and a great re-centering capability. Moreover, austenitic wires can also dissipate energy, increasing the global damping.

Experimental Study, Results and Discussion:

A 2-story, twelve bay existing building was used for the experimental testing. In order to avoid any interaction with the structural elements, all internal and external infill masonry panels were demolished. The twelve bays were divided into individual modules so that single bay structures could be tested for different retrofitting methods and configurations. The module, in the presented test in the paper, was strengthened with the SMA bracing system in its weak direction.

Pushover analyses were conducting using the DRAIN-3DX finite element program in order to evaluate the number of wires required in each brace. The final number of 1 mm diameter SMA in each device was found to be 64. Moreover, the length of the wires was also calculated from elongation of the braces and their deformations.

Cyclic dynamic and dynamic release tests were performed on the retrofit structure

From tests results, there was some small energy dissipation in the structure, due to both the characteristics of the SMA devices and flexibility of the RC frame, despite high imposed displacement. The structure exhibited excellent re-centering capacity and no residual deformation when the load was removed.

Representative Figure of the Structure:

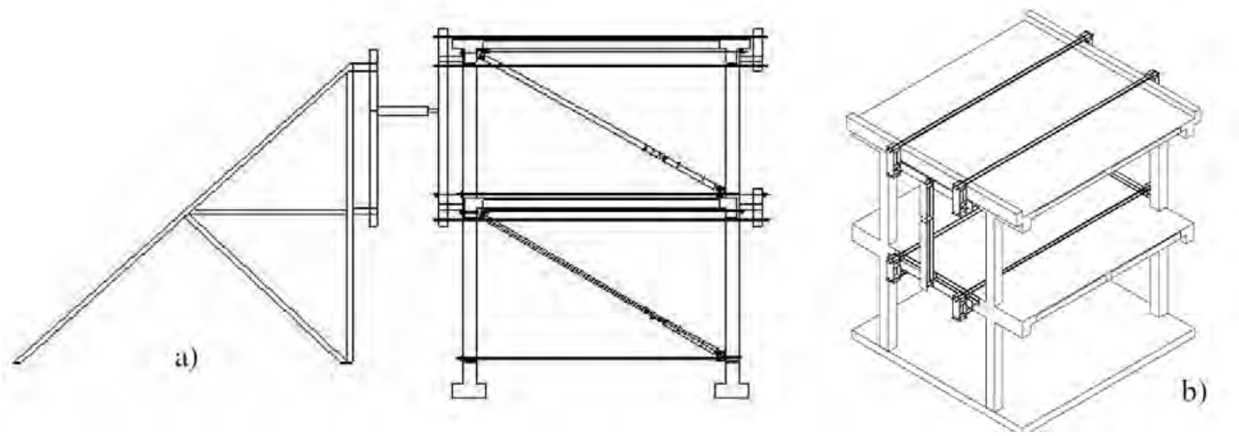


Figure 60 RC Frame Upgraded with SMA Re-centering and Dissipating Braces [after Dolce et al. 2004]

5.8. Carden, L.P., Itani, A.M., and Buckle, I.G., 2006

"Seismic Performance of Steel Girder Bridges with Ductile Cross Frames Using Single Angle X Braces"

Introduction:

The authors evaluate the performance of I-girders with ductile end cross frames that use single angle X braces acting as structural fuses. Shake table experiments were conducted in this study. Component testing was also conducted on single angles to determine their yield strengths for comparison with the stresses induced in the system testing.

System Concept:

Employing ductile members to brace the transverse direction of bridges is intended to reduce the base shear on the substructure, where damage is more difficult to identify than the superstructure. The authors evaluate if single angles are ductile enough to reduce base shear through energy dissipation from their yielding. After the ductile members yield, they are intended to harden, but also to experience post-yield stiffness degradation. This allows them to deform greater amounts without breaking, acting as energy-dissipating fuse elements.

Experimental Study, Results and Discussion:

A bridge model was tested under reverse static loading and a shake table with single angle X bracing welded or bolted to a plate connecting the bridge girders. A double angle served as a bottom chord, with a top chord in some tests. The top and bottom chord served as rocking mechanisms to allow for large girder drifts. Component testing also occurred on seventeen single angles.

Component testing on the angles showed initial failure in tension, followed by hardening. In compression, the angles buckled and immediately lost most of their strength.

The full bridge model was found to have greater shear forces when only elastic cross members were used. The base shear with ductile single angle cross members was 78% of that with elastic members for seismic loading of 1.5 times El Centro. The base shear was even further reduced with larger scaling of the forces of El Centro. Large drifts occurred with the single angle X bracing, but the self-centering capabilities of the top and bottom chord limited residual drifts.

It was also found that the concrete deck would not be distressed if minimum connection between the deck and girders is detailed.

Representative Figure of the Structure:

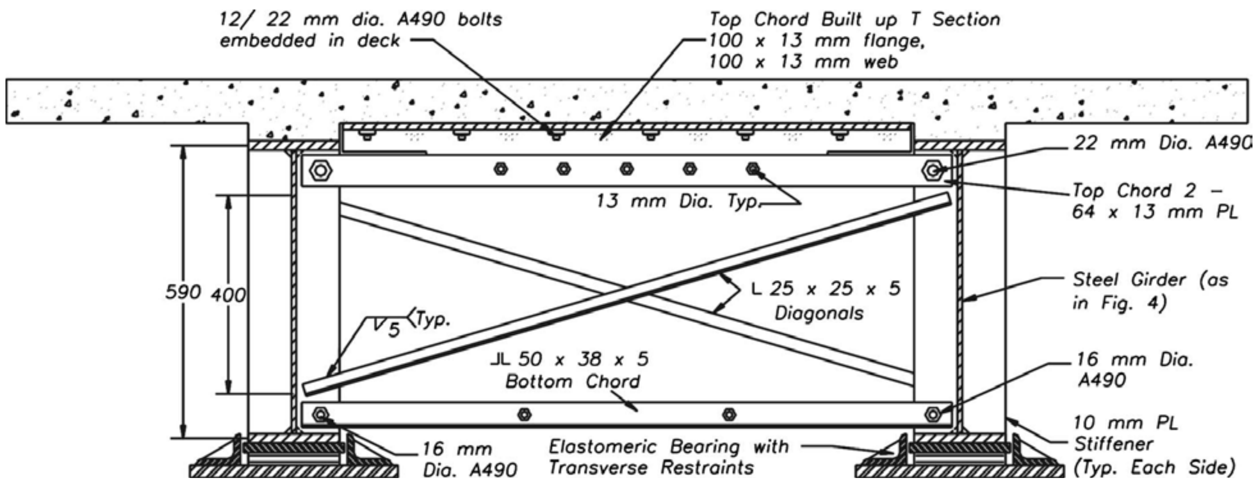


Figure 61 Single Angle X Braces on Bridge Model [after Carden et al. 2006]

5.9. Tremblay, R., Lacerte, M., and Christopoulos, C., 2008

"Seismic Response of Multistory Buildings with Self-Centering Energy Dissipative Steel Braces"

Introduction:

In an analytical study, the authors compare the response of 2, 4, 8, 12, and 16-story buildings to seismic excitation with BRBs and SCED bracing members. Incremental static analyses and nonlinear dynamic analyses were performed. The same floor plan was used in each model.

Several studies have shown that structures with BRBs can often experience residual lateral deformation or the concentration of damage at some stories. Having another resisting element is key to prevent these from occurring. The purpose of the study was to validate the use of SCEDs as effective energy dissipaters to supplement the use of BRBs on structures.

<u>*System Concept:*</u>

A friction energy-dissipating element connects the braces in this SCED system. Pretension fiber tendons are also included to act as a self-centering mechanism. When the brace is forced into tension or compression, the tendons are elongated. The tendons exhibit a flag-shaped hysteretic response and thus full re-centering is possible.

<u>*Analytical Study, Results and Discussion:*</u>

2, 4, 8, 12, and 16-story buildings were evaluated with both BRBs and SCEDs. A 2D model was used with a rigid diaphragm between the braces and columns. The SCED to brace connection was modeled as two springs in series. The models were excited with ground motion at 50, 10, and 2% of the fifty year hazard level in Los Angeles.

It was shown that the peak story drifts was reduced using the SCED, resulting in better resistance to collapse. The activation and response of the SCED as an energy-dissipating mechanism is more sudden, however, thus floor acceleration pulsing occurs that could damage stiff structural and nonstructural components of the building. Of note is that the results are more pronounced with an increase of stories. On lower stories, both systems experience greater deformations than is predicted by design code, thus it is recommended by the authors that the response modification factor be reduced to 5 for low level structures.

<u>*Representative Figure of the Structure:*</u>

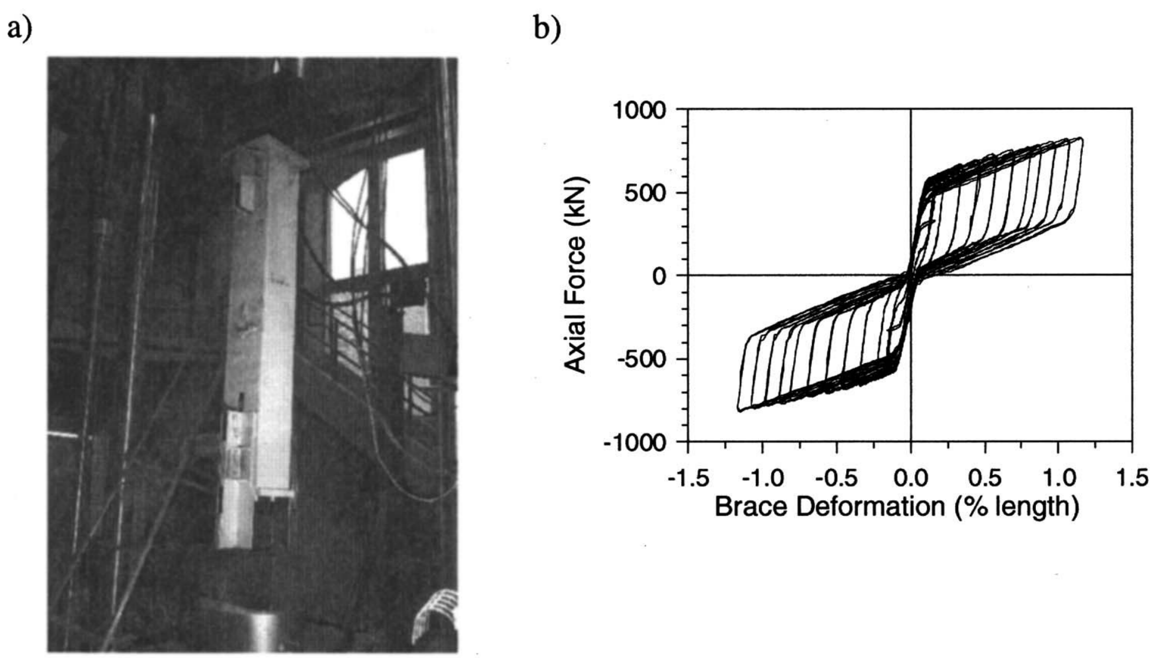


Figure 62 (a) Brace Configuration (b) Flag-shaped Hysteretic Response of SCED [after Tremblay et al. 2008]

5.10. Zhu, S. and Zhang Y., 2008

"Seismic Design of Steel Concentrically Braced Frame System with Self-Centering Friction Damping Braces"

Introduction:

The authors propose a special type of bracing element termed a SFDB. A seismic design procedure for the SFDB is then developed. The purpose of this structural system is to minimize residual drifts and create a damage-free structure after frequent and design based earthquakes. SFDB are typically installed in CBF buildings as part of the bracing system which resisted lateral loads. SFDB frames are capable of achieving a seismic control level comparable to that of buckling-restrained braced frames, while having significantly reduced residual inter-story drift after earthquakes. SFDB devices are reusable after frequent design based earthquakes. In order to explain the displacement based seismic design approach for SFDB frames, two design examples are used: a 3-story and a 6-story SFDB frame.

System Concept:

The SFDB re-centers itself through the use of superelastic SMA wire strands. Moreover, it can also dissipate energy through friction.

Design Procedures, Results and Discussion:

A 3-story and a 6-story SFDB frame were used as prototype buildings for displacement-based seismic design approach. Non-linear dynamic analyses were applied to two prototype buildings. In the design steps, the drift target in the design of SFDB frames was selected based on primary performance objectives. Both high damping and low damping were considered for hysteretic behavior of the SFDB. Frames were also designed both with (SFDB) and without (SFDB-NF) friction dissipation at the sliding surface. The 3-story building, including both the SFDB and SFDB-NF frames, could meet the design target performance. The 6-story building, underestimated the peak inter-story drift ratios and brace ductility demands for both the SFDB and SFDB NF frames. Nonlinear dynamic analyses results show that SFDB frames designed using the DBD procedure can achieve the target displacement parameters with a high degree of accuracy, however, caution should be exercised in the design of medium-rise buildings since the design procedure tends to underestimate values of maximum story drift ratios and brace ductility demands.

5.11. Christopoulos, C., Tremblay R., Erochko J., and Choi H., 2008

"Self-Centering Energy Dissipative Bracing System for the Seismic Resistance of Structures: Development and Validation"

Introduction:

The authors examine buckling-restrained and self-centering bracing systems. In this paper, new PT-SCED braced frame technology is described, then, results from quasi-cyclic and dynamic seismic testing are conducted to verify the behavior of the proposed system. The purpose of this system is to eliminate damage to structural elements and minimize residual deformations by means of a brace member which can undergo large axial deformations.

System Concept:

The structure in the study consisted of two structural steel members, pre-tensioned tendons and an energy dissipative mechanism. The fuses used were a buckling restrained and a self-centering brace. Energy dissipation is provided by friction and the members achieve a flag shaped hysteretic response. Square steel tubes were selected for the structural members due to their high compressive strength. A smaller tube is inserted into a larger one to form a compact bracing member. The fuse element can be replaced after yielding due to a bolted connection to the frame.

Experimental Study, Results and Discussion:

Nonlinear dynamic analyses of building structures from 2 to 12 stories were performed to evaluate the performance of an SCED braced frames with friction energy dissipation. Cyclic quasi-static and dynamic tests with simple shear beam to column connections show similar peak inter-story drifts in SCED and BRB braced frames, but less damage concentration and smaller residual lateral deformation occurs in the SCED system. Moreover, it was observed that the residual roof displacement at the roof for BRB frame is more than SCED frame.

Analytical Study:

In an analytical study, an SCED braced frame system was evaluated and compared with a frame with BRBs using nonlinear time-history analysis of typical office buildings with different story heights. The SCED system exhibits uniform distribution of the deformation demand along the building height, together with lower residual deformations than the frame with BRBs.

Representative Figure of the Structure:

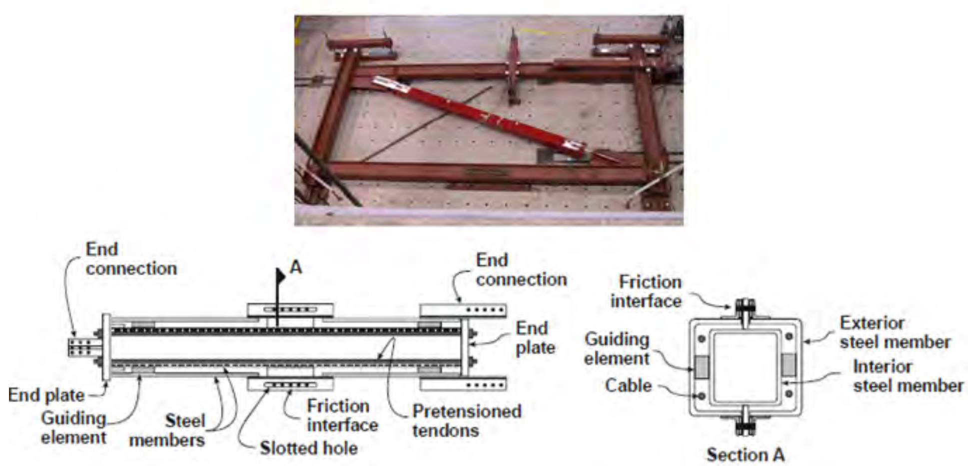


Figure 63 PT-SCED Braced Frame [after Christopoulos et al. 2008]

5.12. Takamatsu, T., Tamai H., Yamanishi T. and Matuo A., 2008

"Rehabilitation of Steel Structure by Means of Wedge Device"

Introduction:

The authors propose an energy absorbing wedge device to be used in structures as an earthquake resistance element. In this study, new structural elements: a non-slip-type column base, a non-compression brace, a self-centering beam-to-column connection and a non-compression knee-brace were studied under cyclic loading to clarify their earthquake-resistant performance, restoring force characteristics and applicability to rehabilitation.

System Concept:

Non-Slip Type Column-Base: A wedge device between the nut and the base plate prevent slip behavior. Any gap generated between the nut and the base plate due to plastic elongation of the anchor-bolt can be eliminated by the wedge moving into the gap under spring compression. The anchor-bolt can absorb plastic energy without pinching behavior.

Non-Compression Braces: This structure consists of a slender rod with tensile-connected ends equipped with a wedge device. One end of the brace is pinned and the other (with the wedge device) is designed as a roller moving only in the compressive direction. The brace can thus resist only tensile force. The plastic deformation capacity and energy absorption capacity of the non-compression brace depends on the sliding displacement of the wedge.

Non-Compression Knee-Brace: This specimen consists of a rigid connection with non-compression knee braces.

Experimental Study, Results and Discussion:

Horizontal actuators were used in all experiments to laterally load the systems.

Non-Slip Type Column-Base: In this test, anchor bolts are considered as the yielding elements, and the base plate, column member and foundation are considered as elastic elements. Test results show that the column base was able to self-center until the elastic limit of rotation was exceeded. No looseness was generated in the column base due to the lack of a gap between the nut and base plate.

Non-Compression Braces: Under cyclic loading tests, the braced frame showed spindle-type restoring force characteristics at each loading cycle, and constant elastic-stiffness curves.

Non-Compression Knee-Brace: Members other than the knee-braces showed behavior in the elastic region. Under cyclic loading, the restoring force characteristics became bi-linear curves.

Representative Figure of the Structure:

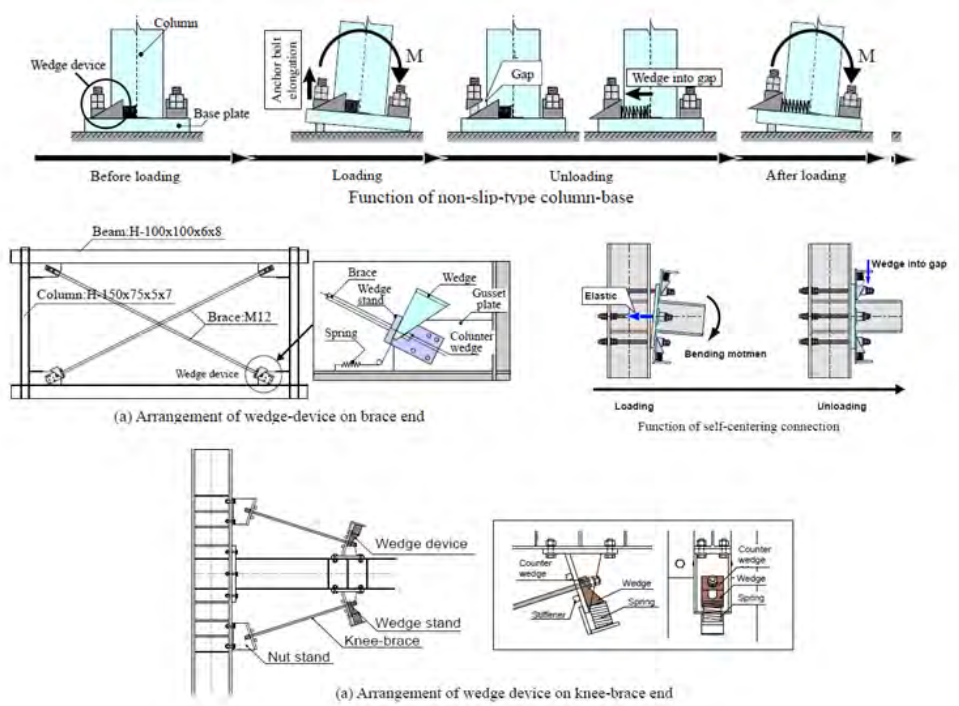


Figure 64 Different Usage of Wedge Devices [after Takamatsu et al. 2008]

5.13. Qian, H., Li H. N., Song G., and Sun L., 2008

"Shaking Table Tests on Steel Frame Building with Innovative Hybrid SMA Friction Devices"

Introduction:

The authors discuss the effectiveness of an innovative energy dissipation device: the HSMAFD. Shake table tests were conducted with and without this passive energy-dissipating device that also exhibits re-centering capabilities.

SMAs dissipate energy through the martensitic phase transformation in the metal instead of yielding, sliding friction, or deformation of viscoelastic solids or fluids. Moreover, SMAs have unique properties such as the superelasticity effect, extraordinary fatigue resistance, corrosion resistance, high damping characteristics and a temperature dependent Young's modulus. These properties make them particularly suited for seismic.

System Concept:

HSMAFDs are composed of pre-tensioned superelastic SMA wires and friction devices. The superelastic wires mainly performed a function of re-centering due to the large restoring force that returns them to their original shape. They also dissipate energy through their hysteretic response. The friction devices serve as the main energy dissipaters of seismic energy by relative sliding between friction plates.

The hysteretic behavior of the HSMAFD includes re-centering and energy-dissipating features. With the increase of the displacement amplitude, the energy dissipation per cycle increases almost linearly, while the secant stiffness and the equivalent damping decrease.

<u>*Experimental Study, Results and Discussion:*</u>

A scaled 3-story steel frame with HSMAFDs was subjected to cyclic loading. Three earthquake historical records were used. The results showed that HSMAFDs were effective in suppressing the dynamic response of building structures subjected to strong earthquakes by dissipating a large portion of energy through their hysteretic deformation response. From the test results, the fundamental frequency of the structure increased more than 50% after HSMAFD were installed. The energy-dissipating system thus provided supplemental stiffness to the original structure.

<u>*Representative Figure of the Structure:*</u>

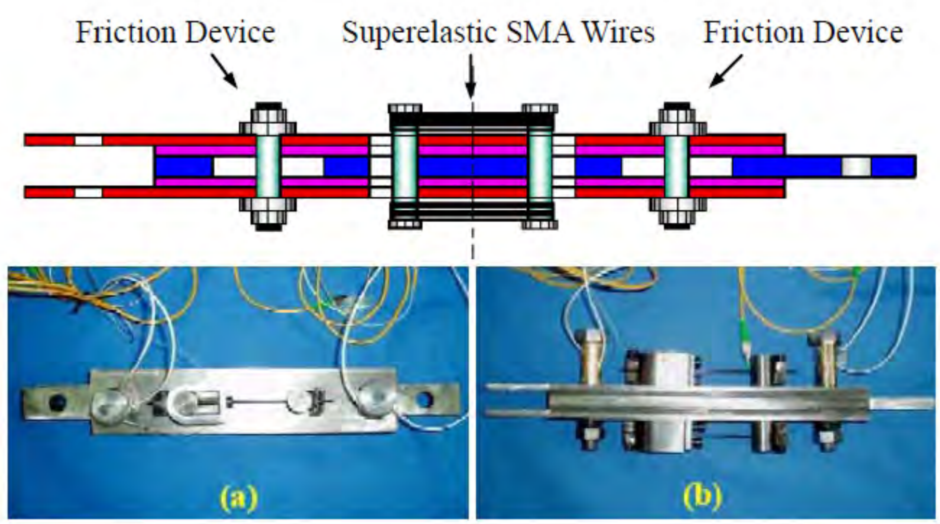


Figure 65 HSMAFD [after Qian et al. 2008]

5.14. Liu, J., Chi H., and Garlock M., 2008

"Design and Analytical Validation of Post-Tensioned Column Bases"

<u>*Introduction:*</u>

The authors explained post tensioned column base in this paper; in terms of system concept, design considerations for the PT column base connection based on a performance-based design approach, and evaluation of PT column base connections, using validate finite element models. A seismic resistant post tensioned steel frame system was developed as an alternative to a welded steel moment frame system. The PT column base connection allows for self-centering behavior of columns, while welded connections do not.

System Concept:

The components of PT column base are PT high strength bars, buckling restrained steel plates, reinforcing plates, keeper plates and shim plates. Buckling restrained plates and keeper plates are welded together. Post-tensioned bars are anchored between half-height of the first story columns to close to the bottoms of the below-grade columns. The initial flexural stiffness before gap opening and post stiffness after gap opening at the PT column bases are associated mainly with the initial level of post-tensioning force and the axial stiffness of the post-tensioned bars.

In the PT frame, the softening behavior of plastic hinges at beam-column connections is replaced by gap opening. So, beam-column connections essentially remain undamaged, provided that beam local buckling is delayed enough to achieve the desired level of rotation. In order to eliminate the damage in columns as well as to enhance the self-centering behavior of the PT frame, a PT column base connection at grade level has been proposed for use in the PT frame.

Design Consideration and Evaluation of PT Column Base Connection:

The strength of the PT column base connection is determined by yielding of the post-tensioned bars; and the limit states at the PT column base connections are defined corresponding to the level of ground motions. The decompressions at PT column base connections and yielding of buckling restrained steel plates were allowed under the Design Basis Earthquake. Also, minor shear yielding of column web near contact interface, which is due to the stress concentration after gap opening, was allowed.

In order to evaluate the design of the PT column base connection, finite element analyses of the PT column base subassembly were carried out. Friction and material plasticization, which are key phenomena of surface contact and separation, were incorporated into the model using computer program ABAQUS. The gap opening causes the elongation of PT bars as well as stress concentration near the bottom of column.

Representative Figure of the Structure:

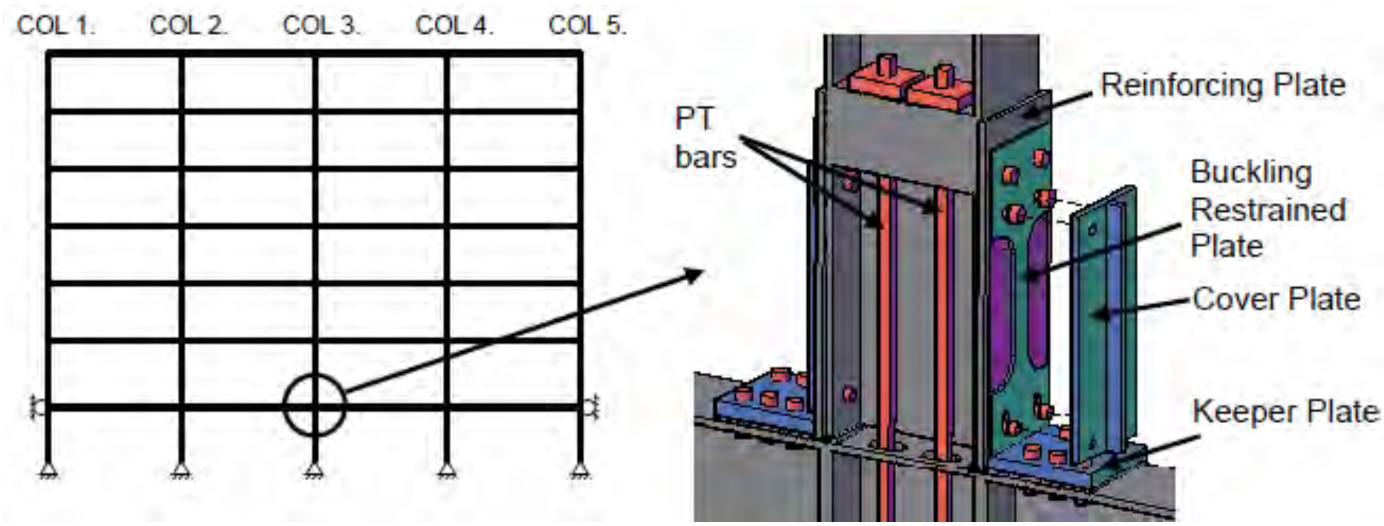


Figure 66 Schematic of PT Column Base Connection [after Liu et al. 2008]

5.15. Kim, H.-J., Christopoulos, C., 2008

"Friction Damped Posttensioned Self-Centering Steel Moment-Resisting Frame"

Introduction:

The paper is proposed a new Self-Centering Friction (SCFR) connection as a new alternative for PT self-centering steel moment frames. The connection eliminates the weld at the beam-to-column interface and provides energy dissipation. Energy dissipation is provided through a bolt-stressed frictional devices consisting of stainless-steel interfaces and new non-asbestos organic break lining pads. PT high strength bars run parallel to the beam which provides the SC capability.

System Concept:

The SCRF is assembly is made up of three main pieces. The PT elements (bars) provide the initial force in the connection. They are anchored outside of the flange faces of the exterior columns and run through the interior column flanges. The frictional energy dissipating devices are located on the top and bottom beam flanges. The last component of the assembly is the backbone frame which consists of the beam and column, providing a capacity envelope for the connection.

As moment is applied to the connection, the initial PT force is overcome and a gap opens at the beam-to-column interface. 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.

Experimental Study, Results and Discussion:

The SCFR assembly 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.

Representative Figure of Structure:

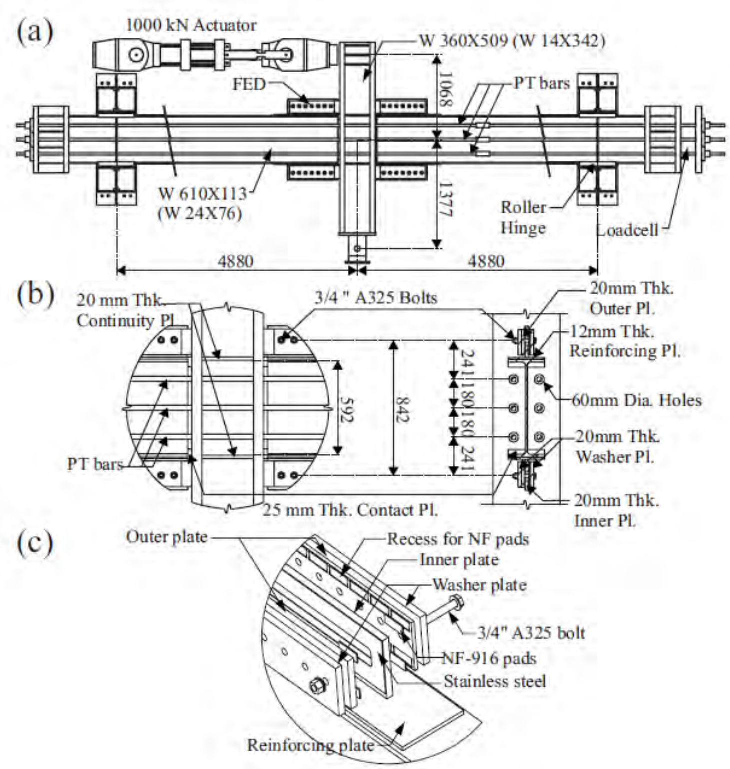


Figure 67 Test setup and SCFR connection detail [after Kim et al. 2008]

5.16. Bruneau, M. and Vargas, R., 2009

“Experimental Response of Building Designed with Metallic Structural Fuses II”

Introduction:

The authors examine the design and performance of a BRB analytically for the purpose of developing simple design procedures for fuse-type energy-dissipating systems. A 3-story sample structure designed with BRBs is then validated experimentally. The system is subjected synthetic ground motions.

System Concept:

The purpose of any fuse system is to concentrate damage in specific structural elements, sparing the remainder of the structure. In this case, BRBs are meant to take all of the damage and be easily replaced, by being connected to the frame with easily removable gusset plates. The BRB consists of a rectangular plate that expands at the ends. The plate is surrounded by tube steel filled with mortar. The tube steel and mortar prevent the plate from buckling. It must yield in either tension or compression. This yielding and subsequent material entry into the inelastic zone dissipates energy. Self-centering occurs after the removal of the load as the BRB is brought back towards its original position through internal forces.

Experimental Study, Results and Discussion:

Two BRBs were tested within a load frame and scaled to 1/3 for geometric quantities, and 1/18 for mass quantities. Ground motion was applied until the shake table had reached its maximum capacity. Uniaxial static tests were also performed on the BRBs so that their behavior could be compared to the dynamic behavior of the BRBs.

It was determined that the surrounding frame behaved elastically throughout the testing while the BRB dissipated seismic energy. Strain gauges were able to measure the deformation of each component. Another important feature of the study was the removability and reliability of the BRB with another BRB. It was found that having a removable eccentric gusset plate to connect the BRB to the frame allowed for easy replacement of the BRB after testing.

Analytical Study:

The analytical study at hand served the purpose of laying out design procedures for structural fuse systems, using BRBs as an example, and verifying the validity of the approach using the experimental study. The process involves defining the allowable drift, determining the elastic period limit, determining a stiffness limit between the required stiffness and frame stiffness, and calculating the required base shear. After these input levels have been set, the metallic fuses are designed for the required base shear, and the actual parameters of the system of designed, the fundamental period of the system is determined, and the seismic response is evaluated through a time-history analysis. This method was found to be satisfactory when compared with the experimental results of the sample BRB.

Representative Figure of the Structure:

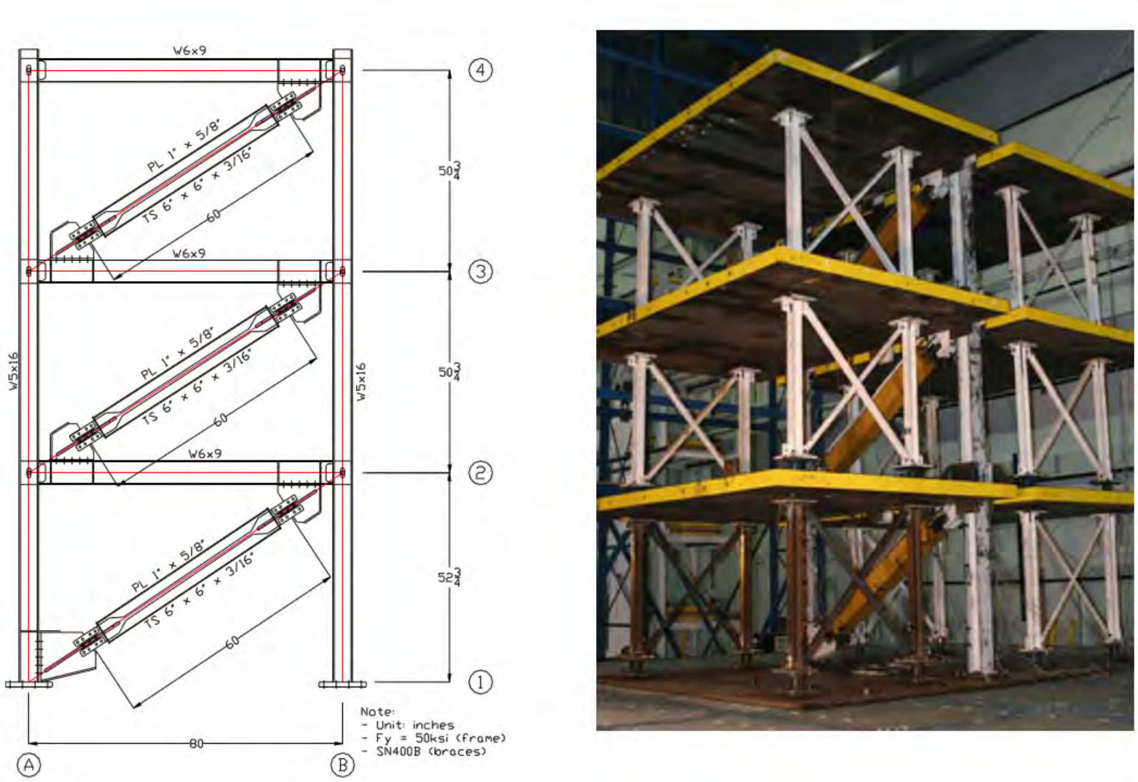


Figure 68 (a) BRB Configuration, (b) Experimental Set-up [after Bruneau et al. 2009]

5.17. Ricles, J.M., Sause, R., Lin, Y.-C., and Seo, C.-Y., 2010

"Self-Centering Moment connections for Damage-Free Seismic Response of Steel MRFs"

Introduction:

This paper presents a self-centering moment resisting frame as an alternative to a conventional moment resisting frame. The design is set up to avoid large residual drive using PT beam-to-column connections for SC. For the system to be desirable it was tested against the design based earthquake for this ability to prevent collapse and sustain minimal damage allowing immediate occupancy performance.

System Concept:

Within a self-centering moment resisting frame the beam-column is characterized by a gap opening and closing during a seismic event. The beams are post-tensioned to the columns by high strength strands of horizontal orientation. The energy dissipation takes place in the beam web friction devices which are attached to the column at the interface.

The PT-WFD has an initial stiffness relative to a traditional welded moment connection. The gap opening occurs when the connection overcomes the imminent gap opening moment and the beam tension flange loses contact with the shim plate at the column face. The PT force increases with strand elongation until yielding. During the unloading, the direction of friction force in the WFD is reversed and the beam tension flange returns to contact with the column.

Experimental Study, Results and Discussion:

A 7-bay, 4-story prototype building located on stiff soil in the Los Angeles area was designed with the web friction devices and tested. The perimeter frames consisted of two 2-bay self-centering moment resisting frames with post-tensioned web friction device connections. The test frame consisted of a 0.6-scale prototype. Hydraulic actuators were used to apply lateral force at each level. A hybrid earthquake simulation was conducted.

Desired connection performance was achieved under the design based earthquake level tests. No significant damage occurred and the WFDs provided reasonable levels of energy dissipation. Self-centering capabilities were also demonstrated.

Representative Figure of the Structure:

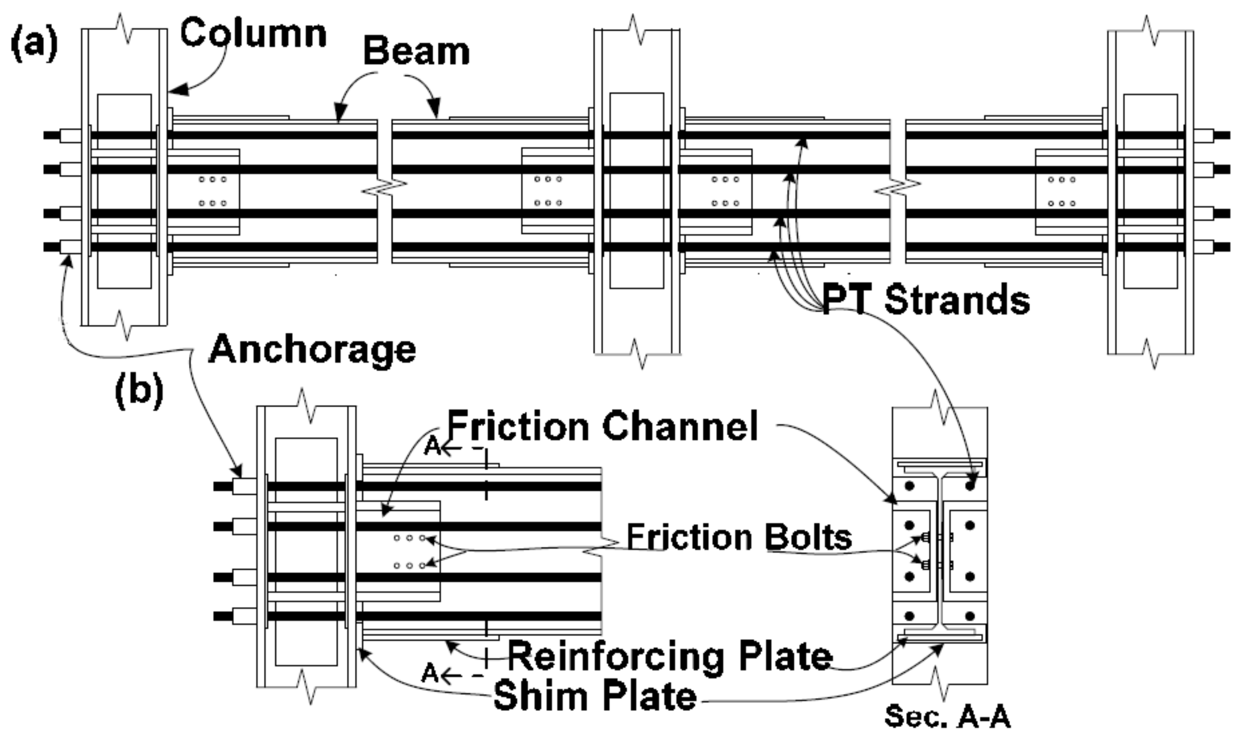


Figure 69 Schematic of elevation of a 2-bay SC-MRF with PT strands and WFDs [after Ricles et al. 2010]

5.18. Wolski, M., Ricles, J. M., Sause, R., 2009

"Experimental Study of a Self-Centering Beam-Column Connection with Bottom Flange Friction Device"

Introduction:

There has been extensive research done in past years on SC-MRF. In general a SC-MRF allows for beam-column connects to develop a gap opening under rotational moments, which is countered by a horizontally orientated PT tendon. The connection allows for minimal inelastic deformation in the beam and columns. This paper presents a SC-MRF with a Bottom Flange Friction Device (BFFD).

System Concept:

The BFFD is assembled with PT high-strength steel strands running parallel to the beam in order to form a new design for beam-to-column connections. The device is composed of a plate with slotted bolt holes that is shop welded to the beam bottom flange and two other built-up angles that are field bolted to the column. Pressed between both sides of the slotted plate and the two column angles are brass friction plates. Energy dissipation happens during the sliding at the faces of the slotted plate and the brass friction plates.

Two advantages of the proposed system is that it does not interfere with the floor slab and when properly designed would not have to be replaced after an earthquake.

Experimental Study, Results and Discussion:

Seven 0.6 scale experimental test were conducted on the SC-MRF with a BFFD. The specimens were subjected to a series of symmetric lateral displacement cyclic cycles. The load was applied to the free end of the beam through an actuator.

The study found that the energy dissipation characteristics were accurately predicted and showed to be reliable. With the PT strands designed to remain elastic and the friction bolts designed to fail in shear after bearing against the ends of the slotted bolt holes, the connection was able to remain damage free under EQ loading.

Representative Figure of Structure:

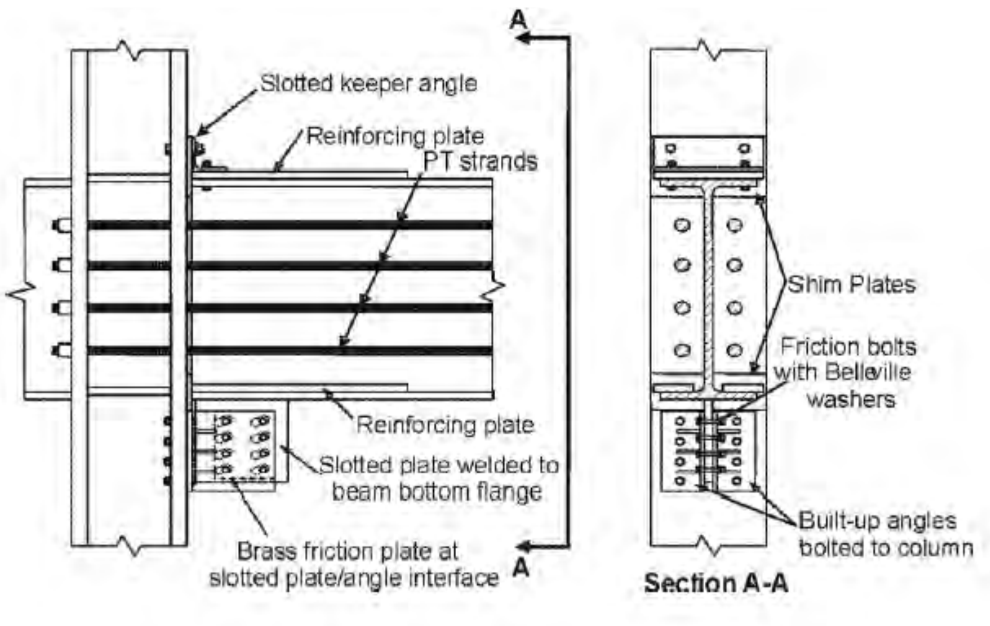


Figure 70 Schematic elevation details for SC connection with BFFD [after Wolski et al. 2009]

5.19. El-Bahey, S. and Bruneau, M., 2010

"Structural Fuse Concept for Bridges"

Introduction:

The research present applies the concept of an energy-dissipating fuse to an innovative multi-column accelerated bridge construction pier concept. The design focuses on two fuse configurations which are added to the bridge bent to increase its strength and stiffness while sustaining the seismic demand through hysteretic behavior. The fuses of discussion are steel plate shear links and buckling restrained braces.

System Concept:

The system consisted of a twin column segmental bridge bent. Each test protocol utilized a series of either steel plate shear links or buckling restrained braces as structural fuses between the columns. The columns were made of Bi-Steel sections and stood at 25 feet. Two static actuators were used to apply the horizontal force.

Experimental Study, Results and Discussion:

The bent rigged with steel plate shear links was loaded to a drift level corresponding with the onset of column yielding to unsure the energy dissipation took place in the fuses. Testing continued until fracture occurred at the base of both columns, where the specimen reached a ductility ration of 4 and drift of 1.5%.

The BRB specimen was loaded in a similar manor and a ductility of 4 was also reached while the BRBs exhibited stable hysteretic behavior.

The 2/3 scale twin column bridge pier bent demonstrated effective dissipation of seismic energy during the quasi-static tests. Both specimens exhibited stable force-displacement behavior until significant accumulation of damage at large drifts. Adding the fuses increased both the stiffness and strength of the bare frame approximately 40%.

Representative Figure of the Structure:

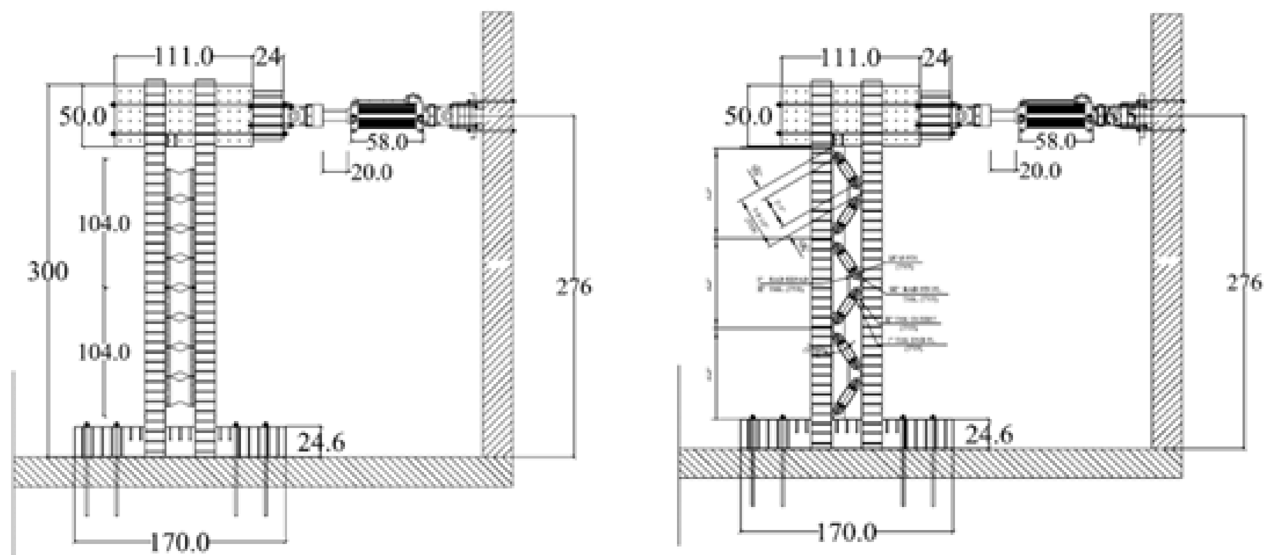


Figure 71 Bridge Pier with SPSLs (left) and BRBs (right) [after El-Bahey et al. 2012]

5.20. Miller, D., Fahnestock, L., and Eatherton, M., 2011

"Self-Centering Buckling-Restrained Braces for Advanced Seismic Performance"

Introduction:

This paper investigates the performance of self-centering buckling restrained braces. These braces provide the ability for a structure to return to their initial position after a seismic event and minimize damage. The research presented is geared to develop an innovative self-centering brace for advanced seismic performance.

Experimental Study, Results and Discussion:

The self-centering buckling restrained brace consist of a typical BRB component with is supplemented with pre-tensioned superelastic NiTi shape memory alloy rods, providing the self-centering. The unit can be substituted for a conventional steel brace or a BRB brace without changing the global structure. This system does not contain many of the challenges associated with PT moment frames or rocking braced frames.

As the brace deforms, the middle and outer tubes act as struts that push the anchorage plates apart. The self-centering force is increased as the anchorage plates move apart. The BRB core yields in tension and compression, the energy is dissipated. The pre-tension selection is greater than that of the yielding force producing the self-centering.

<u>Analytical Study:</u>

A numerical model was created using OpenSees and a SC-BRB was designed for a prototype building matching a 5-story BRBF design example. The model used gap elements to represent contact between the tubes and anchorage plates. Stages were assembled to allow for pre-tensioning. The analysis was tracked for both the buckling restrained brace and the self-centering component.

Specimens were tested using increasing strain cycles. The two variables studied were length of time of the heat treatment and sequence of machining and heat treatment. It was found that strength decreased as heat treatment time increased. The smallest amount of residual elongation occurred when the shape memory alloy bars were heat treated for 60 minutes after machined.

<u>Representative Figure of the Structure:</u>

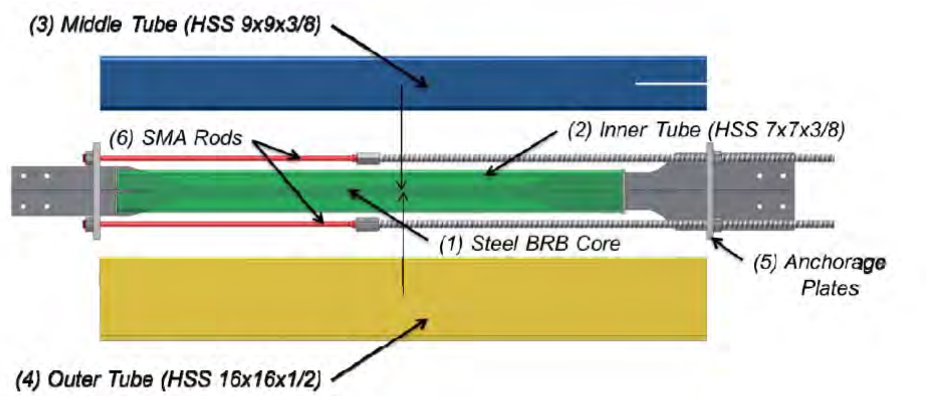


Figure 72 Self-Centering Buckling Restrained Brace [after Miller et al. 2011]

5.21. Sanada, Y., Sashima Y., Sugiura H., 2011

“Development of an Energy Dissipation Device for Prestressed Concrete Members“

<u>Introduction:</u>

The authors propose a new energy dissipation device to be attached to PC members to improve their energy dissipation capacity, something that has traditionally been lower than that of RC buildings. Structural damage in PC buildings can also be reduced by their self-centering characteristics. In order to improve seismic energy dissipation of PC buildings, friction dampers were developed. Several structural tests were performed to verify their contribution to the seismic performance of a PC beam.

Experimental Study, Results and Discussion:

Repeated loads were applied to the damper to measure the induced friction forces under tensile loading. An unbonded PC specimen was prepared to apply the friction damper. Reversed cyclic loads were used. From tests, asymmetric contributions were observed in each loading directions. Damper contributions were different in positive and negative directions due to the different distances between the axis of rotation and center of the damper. The damper also increased residual deformations after unloading, something that could be canceled by releasing the compression force acting on the damper.

Representative Figure of the Structure:

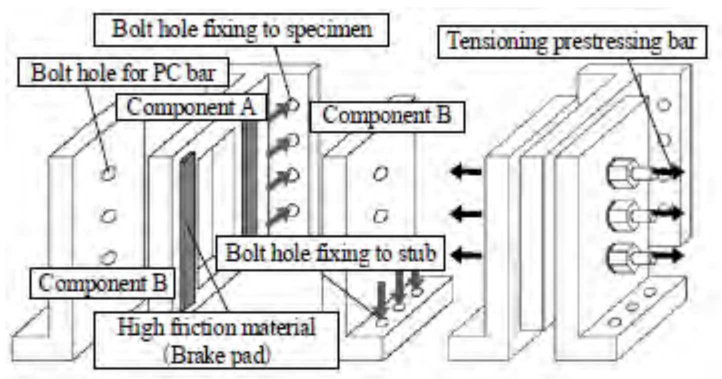


Figure 73 Friction Damper [after Sanada et al. 2011]

6. Structures with Rocking, Self-Centering and Energy-Dissipating Fuses

6.1. Restrepo, J.I., Mander J., and Holden T.J., 2001

"New Generation of Structural Systems for Earthquake Resistance"

Introduction:

The authors discuss design aspects of a new generation of structural systems intended to minimize damage. The paper briefly discusses the results of a test program on precast/post-tensioned structural wall systems. This system is constructed to be low cost while ensuring elastic response in a large earthquake. Structural damage is acceptable if collapse is prevented. Therefore, critical regions on the structure are designed for ductility and energy dissipation. The remainder of the structure is designed for sufficient strength to ensure the energy-dissipating mechanism can develop and be maintained.

The authors address previous design methodology for cantilever walls with unbounded pre-stressed tendons and energy-dissipating devices. The system is then evaluated experimentally for its dynamic response.

System Concept:

The structure is composed of precast concrete walls and unbonded tendons. When a large lateral displacement load is applied, a gap opens at the base of the wall. The opening of a large gap at the base of the wall induces large compressive strains at the corner of the wall. During small amplitude displacements, the joint at the wall-foundation beam remains closed and most deformations take place within the wall panel and the foundation structure. A gap opens as decompression is reached at one end. The response of the wall is non-linear elastic, resulting in little structural damage and residual deformations.

Experimental Study, Results and Discussion:

Experimental tests were conducted on five walls. To enable a comparison of the dynamic response, the backbone moment-curvature response employed in the analyses was identical for both monolithic and jointed wall models. The response of the monolithic wall was modeled using a Takeda hysteresis rule; and the response of the jointed wall was modeled using an origin-centered rule. The monolithic wall was designed for ductile response and the jointed wall was designed to match the capacity of the monolithic wall. Features of testing units were varied to include post tensioned only, incorporating energy dissipation devices in the way of dog-bone bars, being under constant axial load, and being precast.

Experiments showed that jointed walls experienced no residual drifts or structural damage after a major earthquake.

Representative Figure of the Structure:

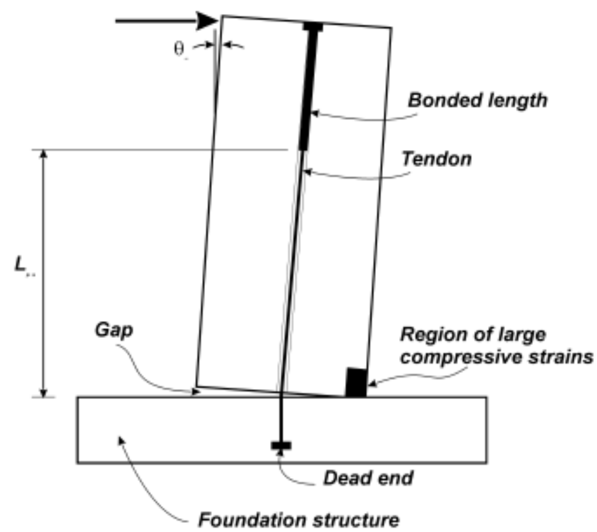


Figure 74 The Walls Pre-stressed with Partially Unbonded Tendons [after Restrepo et al. 2001]

6.2. Palermo, A., Pampanin S., and Calvi G.M., 2004

"Use of "Controlled Rocking" in the Seismic Design of Bridges"

Introduction:

This paper presented alternative solutions for precast concrete buildings based on jointed ductile connections, which was an innovative concept in the seismic design of frame and shear wall systems. The controlling rocking concept was first proposed for precast concrete frames, and then extended to steel frames. The aim of the structure was maximum displacement with negligible residual deformation. In this paper, the seismic response of structural systems with controlled rocking and the response of traditional monolithic systems are compared through push-pull and non-linear time-history analyses on both single and multi-degree of freedom bridge systems.

First, the system was introduced and previous controlled rocking concept applications and tests in bridge piers were explained. After that, behavior of single bridge pier and transverse seismic response of bridge frame with controlling rocking were presented in terms of numerical model, push pull analysis and time-history analysis.

System Concept:

The controlled rocking system at hand is composed of precast elements, PT tendons and mild steel. Pure precast elements are connected though unbonded post-tensioning techniques. Limited damage is expected in the structural elements as they are intended to stay in the elastic range: the inelastic demand is accommodated within the ductile connection. Controlled rocking motion occurs in the connections with the opening of and closing of an existing gap. Unbonded post-tensioning tendons/bars are used for self-centering and mild steels are used to dissipate energy through their yielding.

Controlled rocking and an adequate ratio of self-centering and energy dissipation contributions led to flag-shape hysteresis behavior.

$$\lambda = \frac{M_{pt} + M_N}{M_s}$$

Re-centering and dissipative parts are considered as a fundamental parameter affecting the shape of hysteretic behavior of hybrid connections. The nominator of the above formula was moment capacity due to PT cables/tendons and axial load; and the denominator was moment capacity due to energy dissipative device (mild steel). If λ was higher than 1, self-centering was guaranteed. However, hysteretic dissipation reduced if it was too high.

<u>*Numerical Model, Analysis and Results:*</u>

Lumped plastic models were used for the hybrid connection (controlled rocking) system and monolithic system with a single degree of freedom. A cyclic static analysis was used to investigate their hysteretic characteristics. For the SDOF, there were negligible cracks in the pier element.

The complete bridge model used three dimensional modeling with elastic beam elements and inelastic rotational springs. All bridge piers were designed with the same moment capacity. In the analyses, three bridges (A, B, C) with different geometries were investigated with both the hybrid and monolithic systems. Bridge system A had the most regular configuration and the applied hybrid system showed more symmetrical hysteresis behavior than the monolithic system. Bridge B had a non-regular distribution of pier heights. This resulted in the inelastic demand being concentrated in the central pier, which lead to a more emphasized asymmetric behavior of the monolithic system when compared to the self-centering hybrid connection system. Bridge C had a non-symmetrical distribution of pier heights. Residual drifts were negligible even in the case of monolithic connections due to the higher global flexibility of the bridge piers when compared to the previous bridge systems A and B.

<u>*Representative Figure of the Structure:*</u>

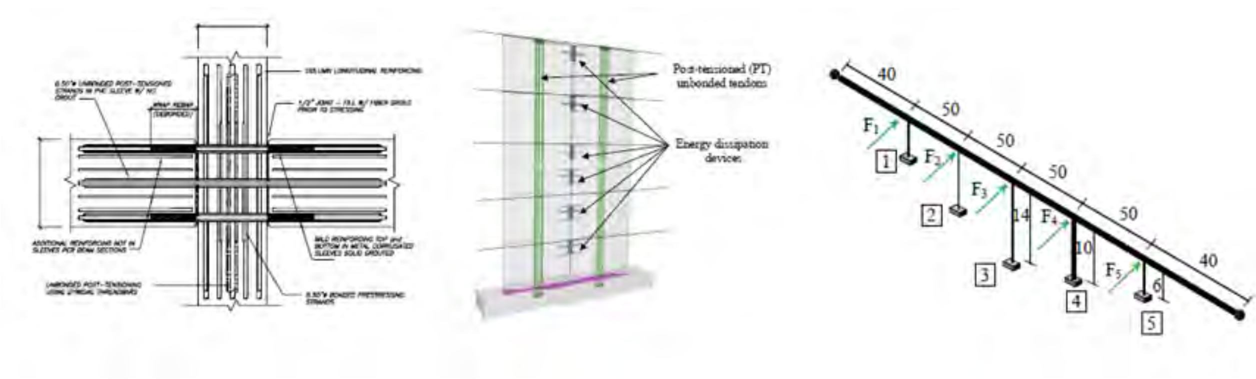


Figure 75 Hybrid Systems for Frame, Shear Walls and Bridge Piers [after Palermo et al. 2004]

6.3. Restrepo, J., Filiatrault J., and Christopoulos C., 2004

"Development of Self-Centering Earthquake Resisting Systems"

Introduction:

In current design approaches, structural systems are designed to respond beyond the elastic limit of the materials and to develop a ductile inelastic response mechanism that will dissipate energy in specific regions of the structural system. One method of achieving this is through the use of self-centering systems. The authors discuss applications of self-centering earthquake resistant structural systems that are intended to prevent excessive damage while emphasizing economic design.

In this paper, after explanation of behavior of self-centering systems, early applications and recent development of the self-centering systems were presented.

Behavior of Self-Centering Systems:

Optimum earthquake resisting systems limit the seismic forces that are transferred to the structure and provide additional damping characteristics that will return the structure to its original position after an earthquake and reduce the cumulative damage. Due to the characteristics of flag shaped hysteretic response of self-centering systems, the amount of energy transferred to the structure is reduced compared to that of the yielding system. Moreover, the system returns to a zero force and zero displacement point in every cycle and at the end of seismic loading.

Early Applications of Self-Centering Systems:

The stepping rail bridge over the south Rangitikei River in New Zealand is an early application of a self-centering system. The self-centering system combined the rocking concept with energy dissipation devices. Base isolation allowed sideway rocking of concrete piers, while the weight of the bridge provided a re-centering capability.

Recent Development of Self-Centering Systems:

Recent developments in self-centering systems for reinforced concrete structures, confined masonry walls, steel structures and bridge structures are explained by the authors. Resisting frame systems pre-stressed with partially unbonded tendons, precast beam column subassemblies, hybrid systems, and post tensioned split rocking wall systems are some example of systems to be applied to concrete structures. In one instance, wall panels are split to allow rocking of the individual panels about their bases. If the weight of the panel is not enough to re-center the structure, unbonded PT tendons can be installed. Grouting reinforcing bars into vertical ducts provides an energy dissipation mechanism.

In coupled wall systems, U-shaped rolled stainless steel plates are used. Observed damage was limited to the loss of two pieces of cover. When design drift was under 2%, there was no visible damage in the frame direction.

Another example of a self-centering system uses unbonded tendons and conventional reinforcement for energy dissipation in reinforced concrete cantilever walls.

Engineers have also used a concrete coupled wall and cantilever walls with vertical joints. This acted as a hybrid system by using PT steel beams and unbonded PT tendons. PT steel beams have been shown to provide a significant restoring force to the walls, thus reducing residual lateral displacements.

In confined masonry walls, columns have been designed for strain control to ensure small shear distortions occur in wall panels, while the wall rocks at the foundation. In this case, energy dissipation devices can be installed at the wall toes.

A hybrid post tensioned connection has been developed in steel moment resisting framed structures. High strength steel strands are used in the connections. They attach to the beams by means of seat and top angles. Shear resistance is provided by friction at the beam-column interface and by the steel angles. In this system, steel angles are the only yielding elements and can be replaced after a major earthquake.

Finally, the authors discuss a self-centering base isolation system for bridge structures consisting of flat sliding bearings and precise positioning fluid dampers. This liquid spring damper is composed of a single column of a compressed fluid. The precise positioning mechanism uses a natural position, ensuing that it stays rigid before and after a shock.

<u>Representative Figure of the Structure:</u>

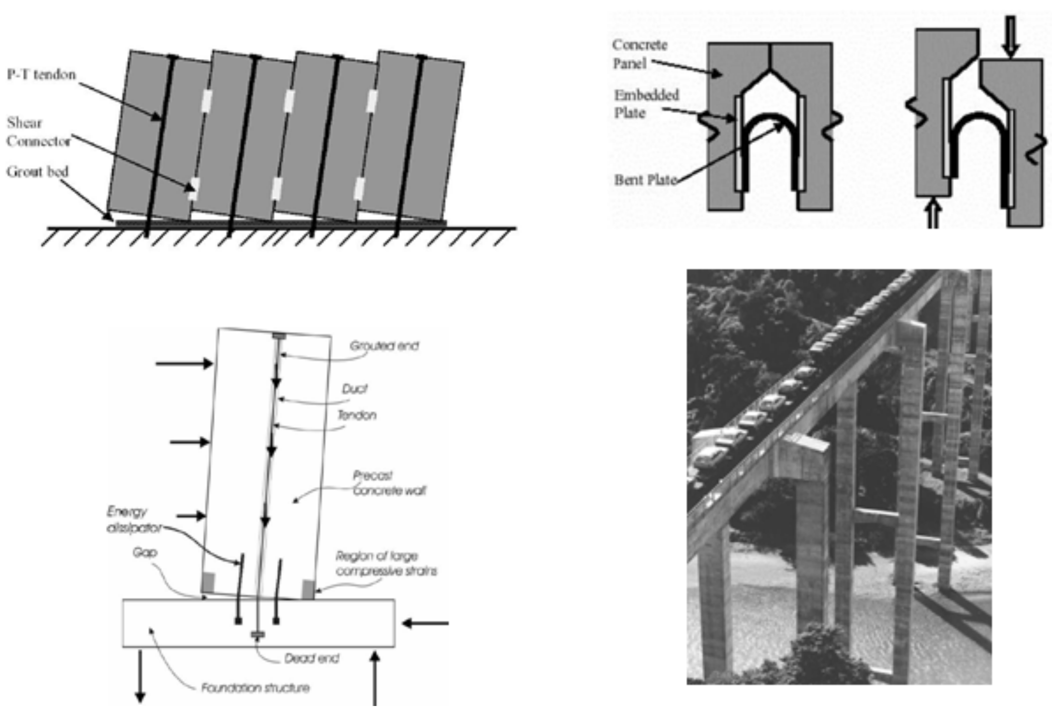


Figure 76 Self-Centering Earthquake Resisting Systems [after Restrepo et al. 2004]

6.4. Bruneau, M., 2007

"Emerging Hysteretic-Based Seismic Systems: Convergence of Ideas in Ductile Steel Design"

Introduction:

In traditional structural systems, ductile behavior has been achieved by the stable plastic deformation of structural members. However, in recent decades, the idea that energy dissipation should occur in the disposable elements has gained steam. These elements are called structural fuses, and a main feature that makes them desirable, is that they can be replaced without causing a disturbance to the rest of the system.

Hysteretic energy dissipation should occur in disposable and replaceable structural elements. This paper reviews emerging hysteretic systems. The authors asses various fuse systems and their advantages over conventional structural configurations. The emerging hysteretic systems explained in this paper are SPSWs, buckling-restrained braced frames, and rocking braced frames.

Steel Plate Shear Walls:

SPSWs are designed to rely on the development of diagonal tension yielding for seismic energy dissipation. Light-gauge cold-rolled and low yield strength steel was used for the infill panel. Reduced beam sections at the ends of the horizontal boundary members were used. This was intended to reduce the overall system demand on the vertical boundary members. By using simple models, an experimental program was developed in order to investigate how to replace a steel panel after a severe earthquake, as well as how a repaired SPSW will behave in a second earthquake. The specimens used before and after replacement showed the same behavior.

Buckling Restrained Braced Frames:

Buckling-restrained braces consist of a ductile steel core inside to yield during tension and compression. The steel core is placed inside a steel casing, and casing is filled with mortar or concrete. Unbonded material is wrapped around the steel core to eliminate transfer of axial force from steel core to mortar. This combination prevents the core from buckling as it yields – hence the name: buckling-restrained brace.

Many uniaxial tests have been conducted on BRBs to show that they exhibit stable hysteresis behavior and a long cycle fatigue life. In order to develop a design procedure, a 3-story frame was designed and investigated. This experimental project also assessed the replaceability of BRBs. Another purpose of the experiments was to examine seismic isolation devices intended to protect non-structural components from severe vibrations. In order to show this, a bearing with a spherical ball rolling in conical steel plate (BNC) seismic isolation devices was used. The BNC was installed on the top floor of a frame model, and its acceleration and displacement were recorded.

Rocking Braced Frames:

It is desirable to design structures able to deform inelastically and constrain the damage to easily replaced ductile fuses to produce stable hysteretic behavior of the structure. In one example, failure or release of the anchorage connections allows a steel truss pier to rock on its foundation. Additional PED devices at the uplift location could control the rocking response while providing energy dissipation. This system was also able to provide an inherent restoring force capability which allowed for automatic re-centering of the tower.

Representative Figure of the Structure:

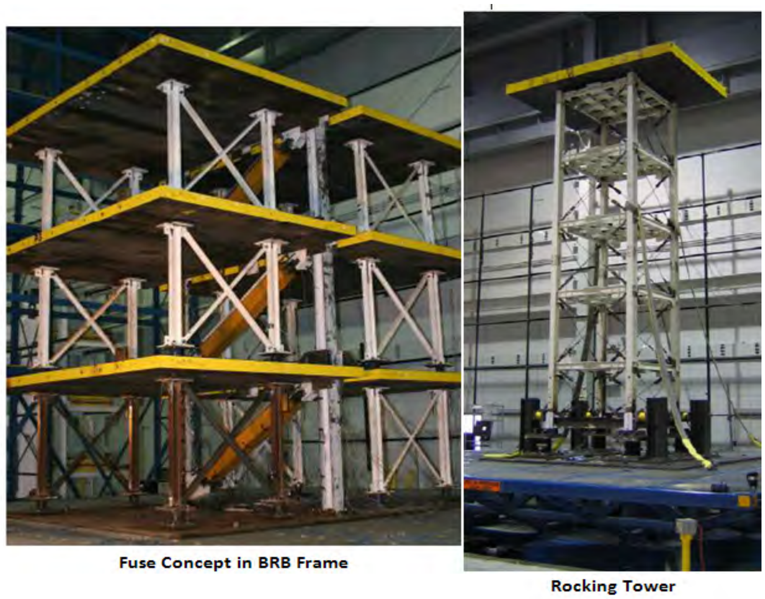


Figure 77 Hysteretic Based Seismic Systems [after Bruneau et al. 2007]

6.5. Restrepo, J. I. and Rahman, A., 2007

"Seismic Performance of Self-Centering Structural Walls Incorporating Energy Dissipators"

Introduction:

A jointed precast cantilever wall is studied for is capability to rock about the foundation without loss of structural integrity. Current design recommends anchoring walls causing plastic hinges to form in response to inelastic behavior. This can result in costly repairs due to structural damage during a seismic event. The proposed system allows uplift upon the foundations which is countered by gravity loading and prestressed unbonded tendons. Energy dissipation is also provided by longitudinal mild steel reinforcement crossing the joint between the walls and the foundations.

System Concept:

Rocking hybrid walls, which are assembled with energy dissipators, allow for a nonlinear elastic response and display a stable flag-shaped hysteretic response. Lateral displacements force a separation gap at the wall-foundation beam connection. Longitudinal Mild steel reinforcement provides significant energy dissipation during this uplift and the gravity load and prestressed unbonded tendons provide the self-centering capabilities.

The energy dissipating devices are labeled as "dog-bones" which consist of machined mild steel reinforcing bars. Energy is dissipated through the section of the bar which is machined at a smaller diameter over a specified length in order to yield at a specified force. The bars are cast into the foundation and grouted into the walls during erection.

The life safety performance objectives for the research are as follows: prevent sliding shear at the wall base, preclude yielding of the tendons, avoid fracture of an energy dissipation device, prevent loss of integrity of the wall, and minimize significant loss of stiffness.

<u>*Experimental Study, Results and Discussion:*</u>

Three half-scale precast concrete wall specimens were created to represent a wall in a 4-story building. Two of the three specimens were cast with energy dissipators. The walls were subjected to quasi-static reversed cyclic loading.

All of the performance objectives for the rocking hybrid walls were closely met. The rocking hybrid system allowed minimal structural damage during a major EQ without residual drifts. The efficiency of energy dissipation was exemplified by a 14% equivalent viscous damping ratio.

<u>*Representative Figure of Structure:*</u>

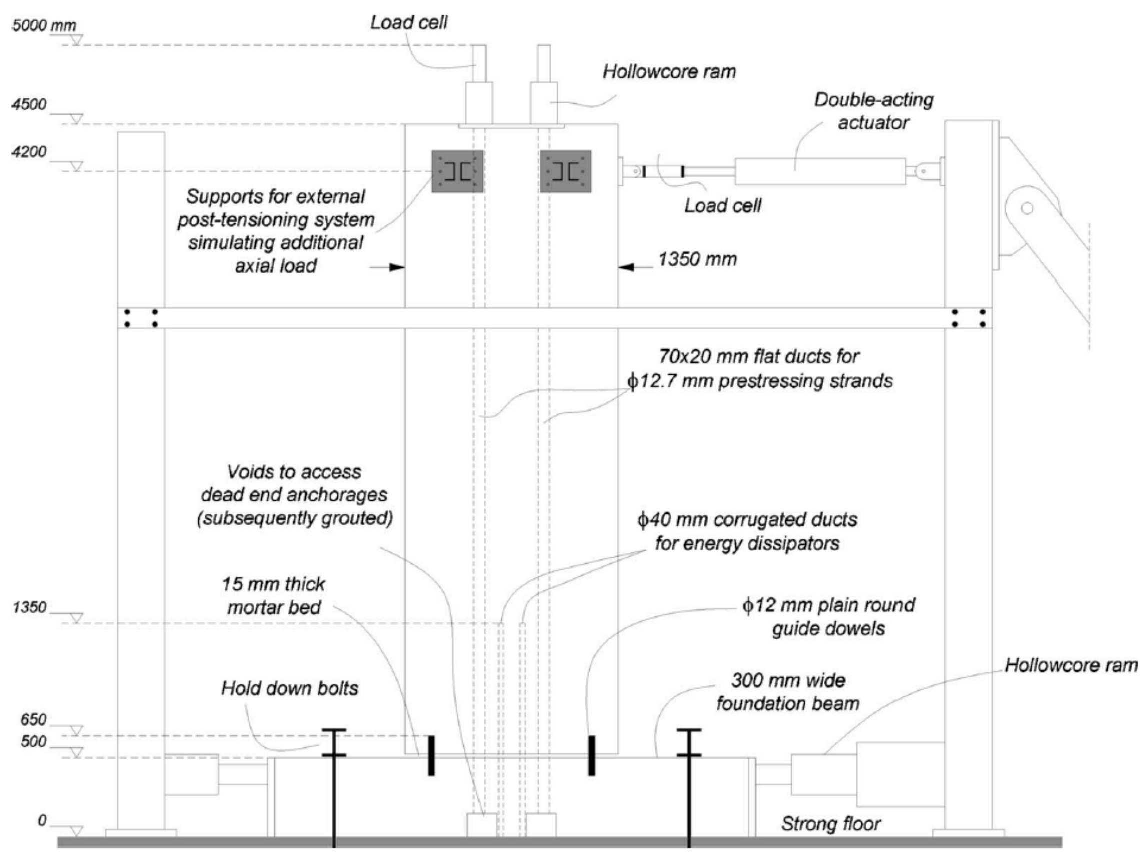


Figure 78 Schematic representation of loading frame [after Restrepo et al. 2007]

6.6. Wang, D. and Filiatrault A., 2008

"Shake Table Testing of a Self-Centering Post-Tensioned Steel Frame"

Introduction:

The authors discuss seismic shake table tests on a 3-story, 2-bay steel frame with a SCPT. In this system, high strength post tensioned strands were implemented in each beam to column connection with sacrificial yielding elements. Two test models, a SCPT and a SMRF, were formed and subjected to various ground motions of increasing intensities. The displacement response, acceleration response and the ED of the two frames were compared. Finally, improved detailing of the SCPT connections was suggested.

System Concept:

In the SCPT steel frame, there is no welding in the connections between the beams and the columns. PT strands are installed along the beam to provide a clamping force at the beam-column connections. These PT strands provided a re-centering capability to the structural system under lateral earthquake loading. The energy-dissipating mechanism comes from four ED bars welded to each beam-column connection. When gap openings between the beam-column interfaces occur under large lateral deformations the ED bars yield in tension and compression and absorb energy.

Experimental Study, Results and Discussion:

Two series of shake table tests were performed on both the SMRF and SCPT frame models. In the first series, a selected ground motion was used, while in the second series, the direction of the ground motion was reversed. Different amplitudes of selected ground motions were used during tests.

It was concluded that the acceleration response was reduced in the SCPT model when compared to SMRF model. It was important to reduce the acceleration response in order to decrease the damage of the acceleration-sensitive nonstructural components and the corresponding economic loss after seismic hazards. After severe earthquakes, only ED bars were yielded in the SMRF structures; while beams were damaged in the SMRF structures. Therefore, the repair cost of SCPT steel frame was less than SMRF. However, an unexpected vertical movement of the beam ends in the SCPT model was observed under severe seismic excitations. In order to avoid this, installation of additional shear tabs in the beam-column joints are suggested.

Representative Figure of the Structure:

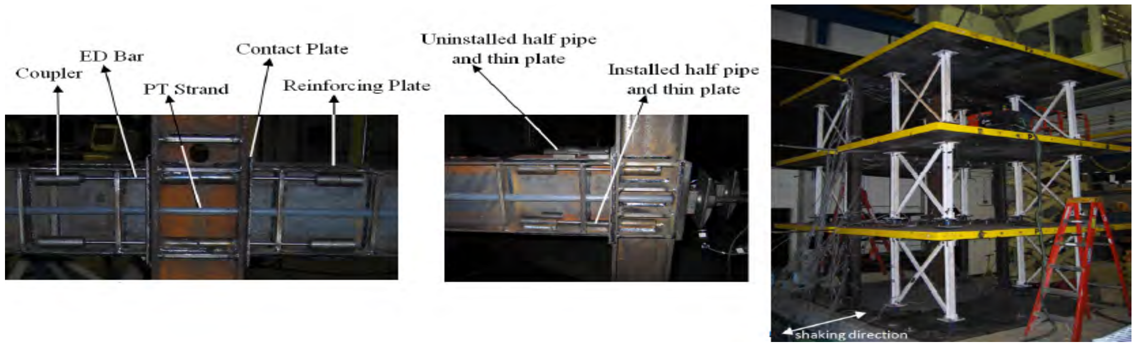


Figure 79 SCPT Beam Column Connections and Frame [after Wang et al. 2008]

6.7. Azuhata, T., Midorikawa, M. and Ishihara, T., 2008

"Earthquake Damage Reduction of buildings by Self-Centering Systems Using Rocking Mechanism"

Introduction:

This paper analytically investigated a self-centering system composed of rocking structural members that are allowed to uplift during an earthquake. This system can prevent steel building structures from experiencing residual deformation after severe earthquakes by using the effect of building's self-weight to re-center. The energy dissipation mechanism is also investigated by means of analytical models. The force-deformation relationship of the rocking structural members is presented using numerical models. The 1995 Kobe earthquake and artificial ground motions were used as input ground motions.

System Concept:

This system is composed of coupled braced units, rocking beams, yielding base plates, and visco-elastic friction dampers. There are two kinds of fuses in the system; yielding base plates at the bottom of each column of the first story and coupled braced units connected with vertical dampers. Yielding base plates work like footing dampers and control uplift response. Connecting dampers improve energy-dissipating performance. In addition, one side rocking beams are used. When the rotational direction at the beam ends is reversed due to earthquake lateral force effect, these edges can uplift freely.

Analytical Study, Results and Discussion:

The linear acceleration method is used for a seismic response analyses. The force deformation relationship of columns, bending-deformation relationship of edge parts of columns, axial force-deformation relationship of braces, shear force-deformation relationship of the vertical dampers were examined. The relationships between the roof displacement and the base shear of the original braced frame model with FIX model and the proposed SCR model was obtained by static pushover analyses. The base shear of the SCR model was seen to be smaller than those of the FIX model. However the corresponding roof displacement of the SCR model is almost equal to or smaller than that of the FIX model. As a result, the self-centering system with rocking structural members was proposed to reduce seismic damage of steel buildings.

Representative Figure of the Structure:

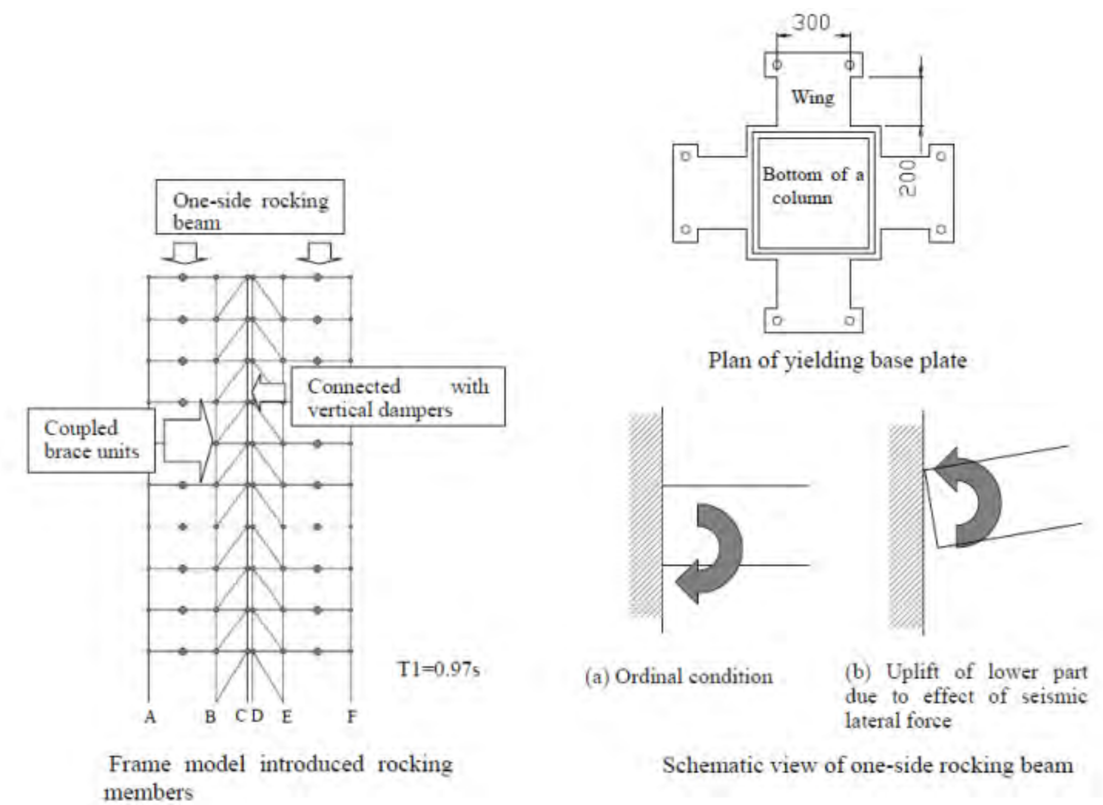


Figure 80 Self-Centering System using Rocking Mechanism [after Azuhata et al. 2008]

6.8. Rodgers, G.W., Dhakal, R.P., Chase J.G., Mander J.B., MacRae G.A., Mander T.J. and Solberg, K.M., 2008

"Investigation of Rocking Connections Design for Damage Avoidance with high Force-to-Volume Energy Dissipation"

Introduction:

The ultimate goal of seismic design is for structures to be able to withstand large earthquakes with minimal or zero damage. This paper discusses a new approach to damage avoidance in the design of connections. In order to avoid damage and strength degradation at the beam-column connections, plastic hinge zones were localized in RC structures to provide ductility. These zones are able to dissipate energy resulting from seismic events. The DAD connections can also provide energy dissipation during seismic events by undergoing inelastic hysteretic response without significant structural damage. Experimental tests are conducted on a 10-story frame to confirm this assumption.

This paper started with the introduction of the system. After that, experimental investigation for RC connections and steel connections were explained with results and discussions.

System Concept:

The high force to volume devices used a bulged central shaft. This shaft induced a plastic flow of lead during shaft motion to provide a resistive force. Emerging high force to volume damping devices could provide equivalent or higher forces than yielding steel fuses. The device response was repeatable on successive cycles and did not show any stiffness or strength degradation. Moreover the devices were not subject to any low cycle fatigue issues and also compact to allow placement directly into structural connections.

Experimental Study, Results and Discussion:

A 10-story RC frame building was used to experimentally investigate the response of three different types of RC connections: an exterior post-tensioned RC connection, a corner exterior post-tensioned connection, and an exterior steel connection. The same structure was designed according to DAD principles and keeping all variables constant. Precast beams and the columns were connected via a post-tensioned system.

Displacement amplitudes were gradually increased throughout the test. It was found that if the resistive force provided by the dampers exceeded the post-tensioning force, the joint could be at risk of losing the ability to self-center following an earthquake. For corner joints, hysteresis loops were asymmetric and overall joint hysteresis loops were substantially larger when the dampers were presented. Using steel joints, hysteretic loops were stable and no strength degradation was observed.

Representative Figure of the Structure:

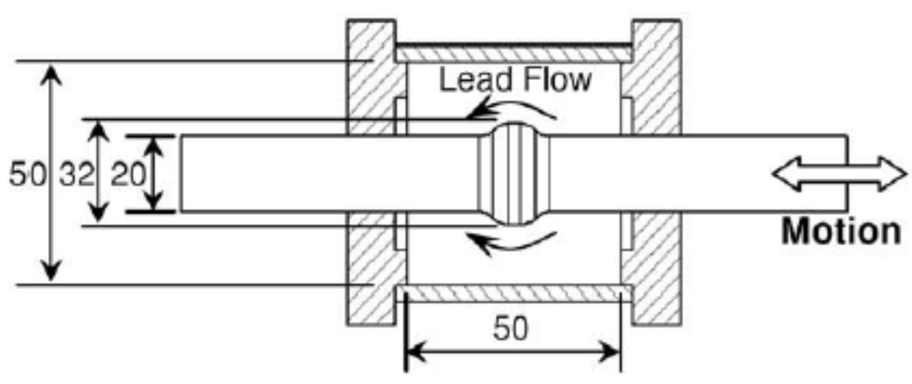


Figure 81 Cross Sectional View of the Device [after Rodgers et al. 2008]

6.9. Pollino, M. and Bruneau, M. 2010

"Seismic Testing of a Bridge Steel truss Pier Designed for Controlled Rocking"

Introduction:

Utilizing controlled rocking, where bridge steel truss piers are allowed to uplift and rock on their foundation, allows for seismic protection. The rocking motion is controlled within allowable limits by displacement-based steel yielding devices or fluid viscous dampers. Prior research has shown that the system can provide a restoring force allowing re-centering and protect existing members of the pier and foundation.

System Concept:

An experimental study was conducted on a scaled model of a generic prototype bridge steel truss pier for a typical two-lane highway bridge. Shaking table test were conducted in the Structural Engineering and Earthquake Simulation Laboratory at the University of Buffalo.

A controlled rocking system is allows pier uplift from the base. The passive energy dissipation devices are located at the base and control behavior response. The specimen contained three sets of steel yielding devices and a set of fluid viscous dampers. It was subjected to past recorded ground motions and compared to previous analytical design predictions.

Experimental Study, Results and Discussion:

The specimen was a 1:5 scale four-legged bridge pier. Base excitation consisted of ground motion histories including the Newhall record from the 94' Northridge EQ and a synthetically generated record. The ground motions were implemented using a shaking table.

It was found in a few instances the analytical prediction of displacement was underestimated by 30-50% of the observed experimental values. Some of the experimental tests also showed significant deviation in the force response when compared to the analytical analysis. It is noted that large axial forces in the pier legs were developed and may require strengthening.

Representative Figure of Structure:

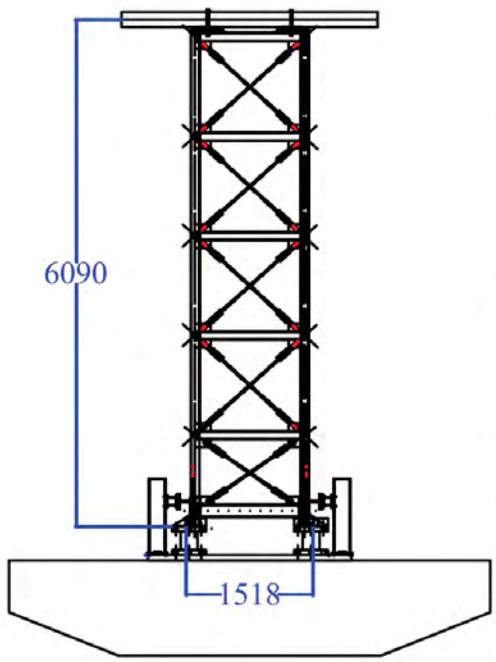


Figure 82 Bridge truss specimen [after Pollino et al. 2010]

6.10. Hamid, N.H. and Mander, J.B., 2010

"Lateral Seismic Performance of Multipanel Precast Hollowcore Walls"

Introduction:

The authors experimentally assess the performance of full-scale precast hollow core walls with longitudinal unbounded pre-stressing tendons. The tendons in this investigation consist of a slender portion to act as a structural fuse under in-plane quasi-static reverse cyclic loading during the tests. The samples are excited to a peak drift of 4%.

System Concept:

The purpose of this system is to resist seismic loads with minimal damage to the surrounding structure. It is thus desired that damage be concentrated in a single replaceable area. The core walls are not rigidly connected at the base, so as to allow for rocking, aiding in deforming the fuse bars. Fuse bars are chosen as the only energy-dissipating element because of their ability to be replaced and energy-dissipating characteristics. The fuse bars are designed with an initial pre-stressing of 50% of the yield stress and as tension only members. Using tension only members prevents any buckling from occurring during compression. This enables the fuse bars to properly yield when the core wall rocks, and provide self-centering capabilities. The use of rubber block spacers between units was also examined in the study.

Experimental Study, Results and Discussion:

Precast hollow core walls with unbounded vertical tendon fuses were tested under quasi-static reverse cyclic loading. It was found that no damage to the walls occurred at the maximum drift of 4% for low story structures. The only damage that occurred was to sealants at the joints, a section that can be easily repaired.

Representative Figure of the Structure:

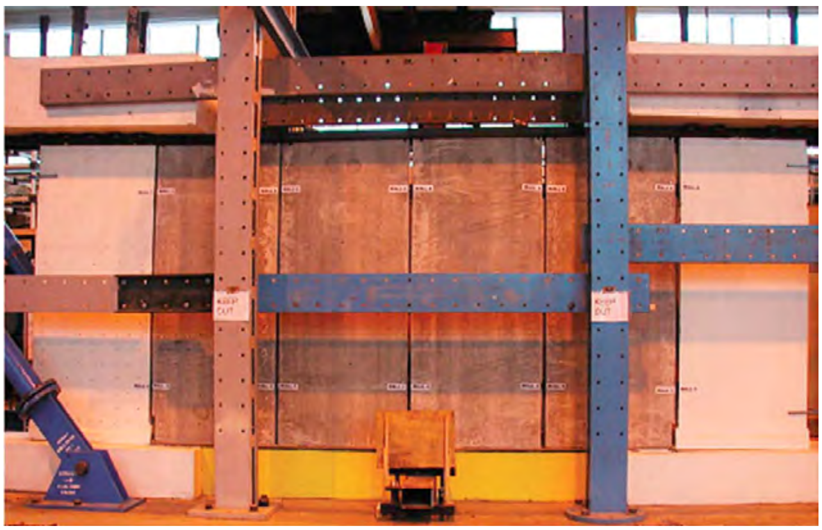


Figure 83 Precast Hollow Core Wall [after Hamid et al. 2010]

6.11. Eatherton, M., Hajjar, J. F., Deierlein, G. G., Ma, X., and Krawinkler, H., 2010

"Hybrid Simulation Testing of a Controlled Rocking Steel Braced Frame System"

Introduction:

The authors discuss a controlled frame rocking with replaceable structural fuses to provide safe and cost effective resistance to earthquakes. The behavior of the controlled rocking systems is explained through the results of quasi-static cyclic and hybrid simulation tests. A computational model is also presented.

System Concept:

This system consists of steel braced frame, vertical PT strands and replaceable energy-dissipating elements. The steel braced frame is design to behave elastically, and is allowed to rock about the column bases. The column base is permitted to uplift but its horizontal motion is restrained by bumpers. Vertical PT strands provided active self-centering forces. The strands are stressed until the point at which additional elastic strain is permitted when the frame rocks. Replaceable structural fuses act as energy-dissipating elements and limit the forces imposed on the rest of the structure. Thin steel plates are used as fuses. Butterfly slits were cut into the steel plates to induce earlier failure of the fuses, and thus early energy dissipation.

The authors determined two important key variables in the design of this controlled rocking system: overturning ratio (OT) and self-centering ratio (SC). OT is intricately associated with the ability of the system to resist lateral loads. SC is the ability of the system to eliminate drift when applied forces are removed. The PT strands and steel shear fuses serve several purposes to address these design variables: they provide overturning resistance, energy dissipation and self-centering capability.

Two configurations of the rocking frame were developed: single and dual frame configurations. In the single frame configuration, the shear fuses are placed at the ground floor connected to a 1-story column at the center of an eccentrically braced frame. When the frame rocks, the center spine of fuses deforms vertically.

In the dual frame configurations, the shear fuses are placed between two rocking frames. When the frames rock, the two inner columns are displaced relative to each other, imposing shear deformation in the fuses. These shear deformations cause energy dissipation, and the vertical PT in the middle of each frame re-centers the dual frames.

The authors postulated a number of fuse and PT configurations. The fuse can be located at the center of the first story bay, with PT at the columns. The locations of the fuse and PT can also be reversed for a second option, with the fuses connected to the columns and the PT in the center of the bay. Finally, both the fuse and PT can be located at the center of the bay.

Experimental Study, Results and Discussion:

Quasi-static cyclic tests were conducted on a 3-story prototype building. Steel plate fuse elements were connected to both frames. A milled base plate with rounded bull nose edges was attached to the base plate of the frame, allowing interior column uplift. A Load and Boundary Condition Box was connected to the top of the specimen through a loading beam and was used to apply the load. Seven dual-frame configuration specimens and two single fuse-configurations were tested.

The controlled rocking system for steel-framed buildings was analyzed using experimental testing and analytical modeling. It was found that damage can be concentrated in the replaceable fuse elements while the frame remains relatively elastic. Also residual drifts were minimized after seismic activity.

Representative Figure of the Structure:

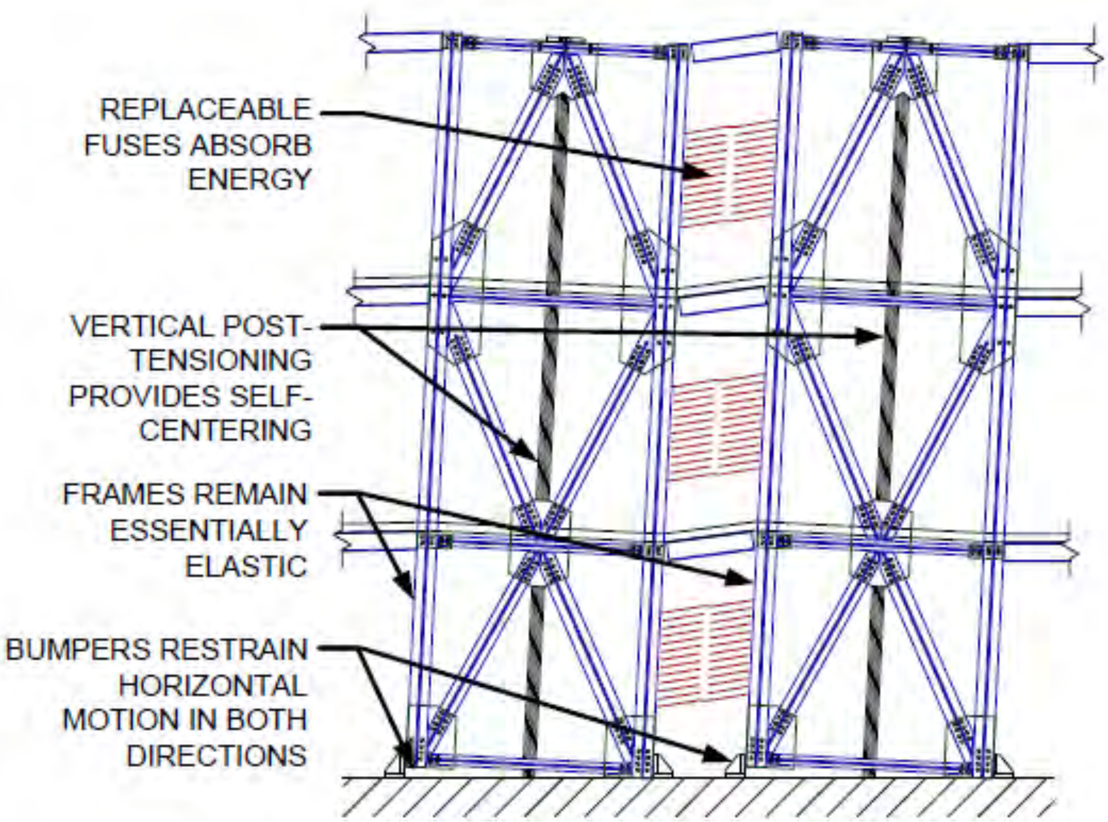


Figure 84 Controlled rocking system in a dual frame configuration [after Eatherton et al. 2010]

6.12. Ma, X., Deierlein, G. G., Eatherton, M., Krawinkler, H., Hajjar, J. F., Takeuchi, T., Kasai, K., Midorikawa, M., and Hikino, T., 2010

"Large-Scale Shaking Table Test of Steel Braced Frame with Controlled Rocking and Energy-Dissipating Fuses"

Introduction:
The paper builds on previous work provided by Eatherton et al. (2010). The presented research outlines the planning, design and preliminary results of a two-thirds scale rocking braced frame tested on the E-Defense facility in Japan.

System Concept:
The structural system is composed of steel braced frames, vertical post-tensioning strands, and replaceable fuses. The frame is able to rock on its base while the seismic energy is dissipated through yielding of the fuses at the base. The frame remains elastic during the motion and the PT strands provide the uplift control and restoring force.

To further the work of Eatherton et al. (2010), large-scale shaking test were conducted at the E-Defense facility in Miki, Japan.

Experimental Study, Results and Discussion:

The controlled rocking frame system was constructed at 2/3 scale. A reusable test bed assembly was used to provide inertial mass and bracing for out-of-plane stability. Three types of fuses were examined: non-degrading butterfly fuse, degrading butterfly fuse, and buckling-restrained brace. The tests were conducted using a scaled acceleration of the JMA Kobe NS and Northbridge Canoga Park ground motions.

Several conclusions were drawn from the experiment. The systems design criteria and constructability was exhibited. Parameters including self-centering, column base rocking and energy dissipation were validated. Also a less complex FEM model provided relatively accurate behavior predictions.

Representative Figure of the Structure:

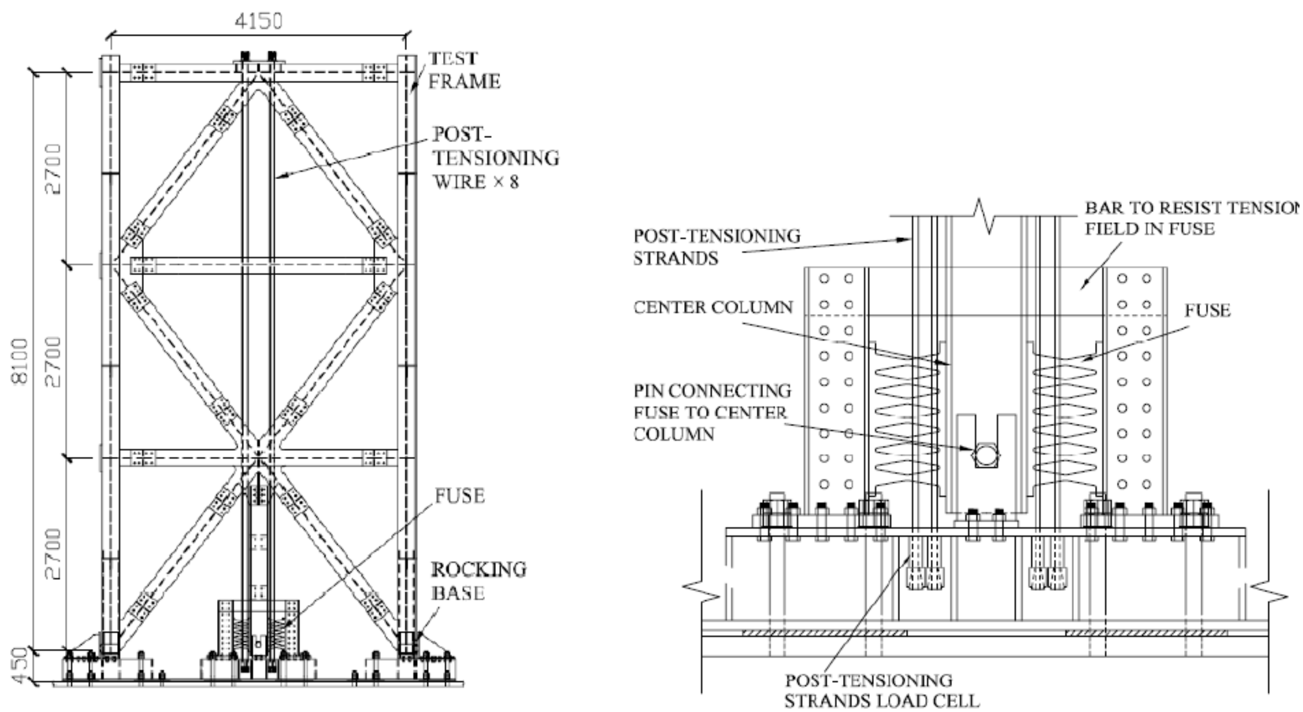


Figure 85 Rocking frame and fuse configuration [after Ma et al. 2010]

6.13. Sause, R., Ricles, J., Roke, D., Chancellor, N., and Gonner, N., 2010

"Large-Scale Experimental Studies of Damage-Free Self-Centering Concentrically Braced Frame under Seismic Loading"

Introduction:

The paper presents the research and development of the self-centering concentrically braced frame. The SC-CBF is introduced as in option to increase ductility and reduce residual drift of CBFs. The summary of design concepts and seismic performance of the test specimen are discussed.

System Concept:

The concept consists of conventionally arranged beams, column, and braces with column base details allow uplift at the foundation. Under low levels of later force, deformation resembles a conventional CBF. At higher levels of lateral force, the overturning moment at the base of the frame becomes large enough for the tension column to decompress and uplift occurs. After uplift, a restoring force is provided by the gravity loads and post-tensioning forces. The PT steel elongates and provides positive stiffness to the later force-later drift behavior.

The configuration chosen for the self-centering concentrically braced frame is placed between two additional columns. Each are attach to the gravity load system of the building. Friction-bearing dampers are designed to allow slip due to relative vertical displacement between the gravity columns and the SC-CBF column. To minimize elongation demand on the PT steel, it was placed at the midbay of the SC-CBF. The vertical distribution strut in the upper story transfers force of the midbay PT steel to the braces over multiple stories.

Analytical Study:

A 4-story office building designed for still soil in Van Nuys, California at a 0.6-scale prototype model. OpenSees was used to perform a nonlinear time-history analysis. A suite of 30 scaled DBE-level recorded ground motion and 30 scaled MCE-level recorded ground motions were simulated. The hybrid simulation was applied by hydraulic actuators through a floor diaphragm model.

The design objectives of immediate occupancy under the DBE and collapse preventions under the MCE were both reached. Analytical predictions also relatively matched the experimental results. It was noted under DBE-level ground motions, no significant structural damage occurred, and under MCE-level ground motion only a small loss of pre-stress occurred. Also in all cases, re-centering was accomplished.

Representative Figure of the Structure:

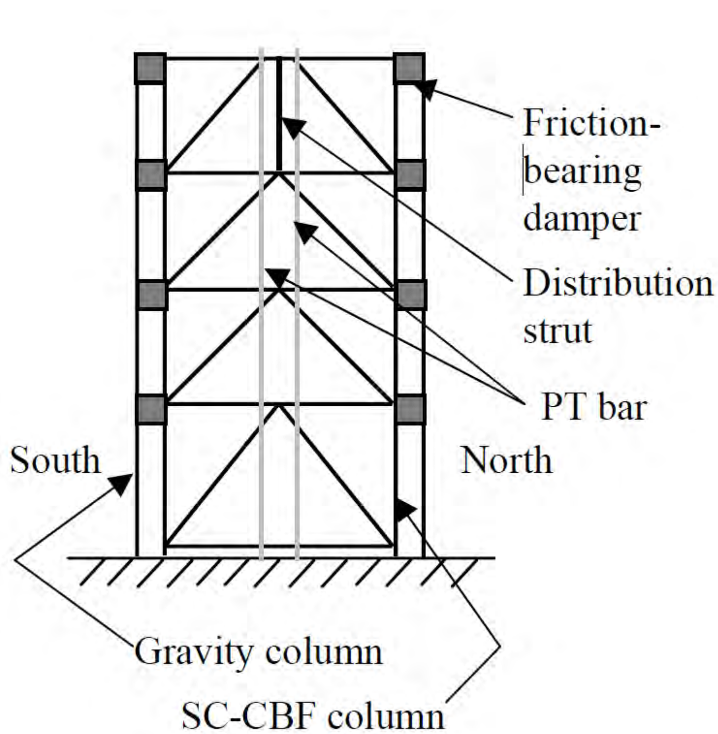


Figure 86 Frame configuration schematic [after Sause et al. 2010]

6.14. Dowden, M. D. and Bruneau, M., 2011

"NewZ-BREAKSS: Post-tensioned Rocking Connection Detail Free of Bream Growth"

Introduction:

This paper mentioned about the details of a PT-RMC concept that could be implemented in steel plate shear wall and moment resisting frame systems. PT-RMC is an alternative MRF connection that provides frame self-centering and limits hysteretic damage to designated energy dissipation elements during earthquakes.

The proposed connection was inspired by a moment resisting connection and named as "New Zealand-inspired-Buffalo Resilient Earthquake resistant Auto-centering while Keeping Slab Sound" (NewZ-BREAKSS).

System Concept:

The connection is composed of light gage web plate, continues steel fish plate, shear plate, stiffener plate, post tensioned and continuity plate. NewZ-BREAKSS eliminates the beam growth by maintaining constant contact of the beam top flange with the column during lateral drift. Moreover, this connection provides a large moment arm from the rocking point to the centroid of the post-tension for maximizing the PT elongation desired for self-centering connections.

The two PT elements need to be anchored independently along the length of the beam, because during frame drift the top flange of the beam is in constant contact with the columns at both ends of the beam. When one of the rocking joint opens and induces PT elongation, the rocking joint at the opposite end of the beam closes and induces PT decompression.

Analytical Study, Results and Discussion:

In order to verify the behavior of the proposed rocking connection and the hysteretic response of SPSWs having NewZ-BREAKSS connections, cyclic nonlinear static pushover analysis was first conducted using the computer program SAP2000.

By means of analytical study, the comparison of formulations developed describing the moment distribution along the HBE and also the system hysteretic response with the NewZ-BREAKSS connection, were done. It was observed that the proposed rocking connection provides re-centering capability as observed by the hysteretic plots.

Moreover, nonlinear time-history analysis was performed in SAP2000 in order to verify the performance of the self-centering SPSW system with the NewZ-BREAKSS rocking connection under a more realistic loading environment due to a ground motion excitation.

As a result, the NewZ-BREAKSS rocking connection provided the advantage of essentially no beam growth, thus mitigating damage to the floor diaphragm and beams while keeping the benefits of PT fames, such as self-centering after an earthquake and limiting inelastic deformations to replaceable elements while the surrounding boundary frame remains elastic.

Representative Figure of the Structure:

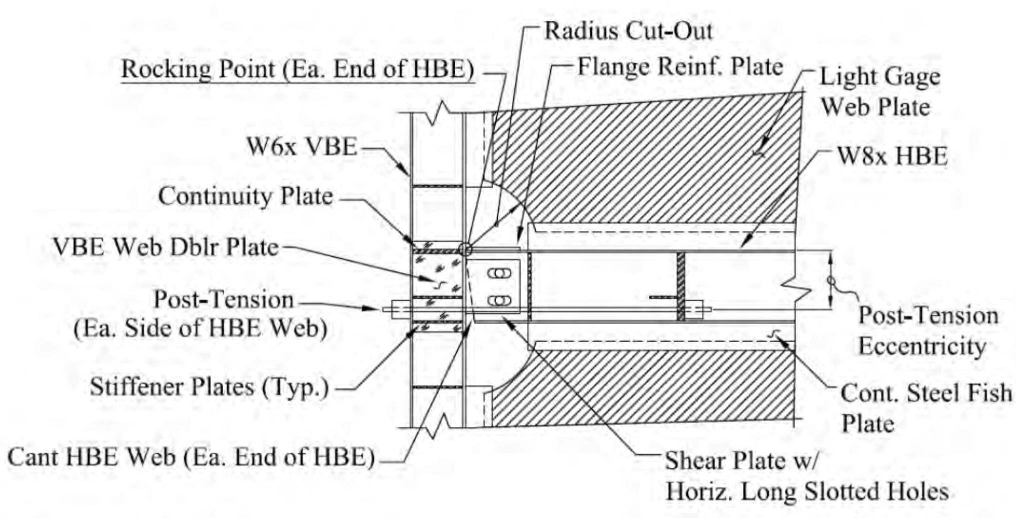


Figure 87 Self-centering SPSW Rocking Connection [after Dowden et al. 2011]

6.15. Clayton, P. M., Berman J. W., Winkley T., and Lowes L. N., 2011

"Seismic Design and Analysis of Self-Centering Steel Plate Shear Walls"

<u>*Introduction:*</u>

This paper presents an overview of the mechanics and behavior of the SC-SPSW system. This system combines the lateral load resistance of a SPSW with the self-centering capability of PT column-beam connections. The authors propose a performance based design procedure and conduct subassembly tests on the SC-SPSW.

<u>*System Concept:*</u>

This system is composed of a steel infill plate with horizontal and vertical boundary elements and PT beam to column connections. The SC-SPSW system resists lateral load and dissipates energy through development of tension field action and yielding in the thin steel infill panel. PT connections provide a self-centering capability to the system. In the SC-SPSW system, PT connections replace typical MR HBE to VBE connections, allowing the connection to rock about the HBE flange and resulting in the formation of a gap. This gap causes the PT strands in the connection to elongate elastically, so damage at the HBE ends is prevented and self-centering is achieved.

The lateral strength of the SC-SPSW was provided by a web plate, which acts as a replaceable energy-dissipating fuse in the system. HBE distributed forces from the yielding web below and above the HBE act in the direction of the diagonal tension field. If the maximum moment occurs along the HBE, it becomes susceptible to the occurrence of in span flexural hinging. Development of the tension field leads to a reduction of lateral load resistance in the SPSW. Occurrence of in-span hinging in the HBE can be prevented by using PT. PT connections can be designed to ensure that the maximum moment occurs at the end of the HBE at a specified drift level before the beginning of HBE yielding.

Combining the SPSW and PT frame results in flag-shaped hysteresis, where self-centering is provided by SPSW and the re-centering capability is provided by the PT frame.

<u>*Experimental Study, Results and Discussion:*</u>

Seven different 3 and 9-story SC-SPSW buildings were designed according to the performance based design approach. 60 ground motions were used on three different seismic hazard levels. The performance of these models was evaluated by measuring the peak story drift, the residual story drift, the occurrence of PT yielding, and the occurrence of HBE and VBE yielding.

The purpose of initial experimental work on the SC-SPSW subassembly was to capture the effects of the interaction of the PT and web plate forces acting on an intermediate HBE, as well as to validate numerical modeling methods. In the tests, the specimen was able to re-center when loaded up to 4% drift with no damage to the frame and PT members, and exhibited the expected flag-shape hysteresis with re-centering.

The proposed performance based design procedure was capable of producing 3 and 9-story SC-SPSWs that could meet the proposed performance objectives at three different seismic hazard levels.

Representative Figure of the Structure:

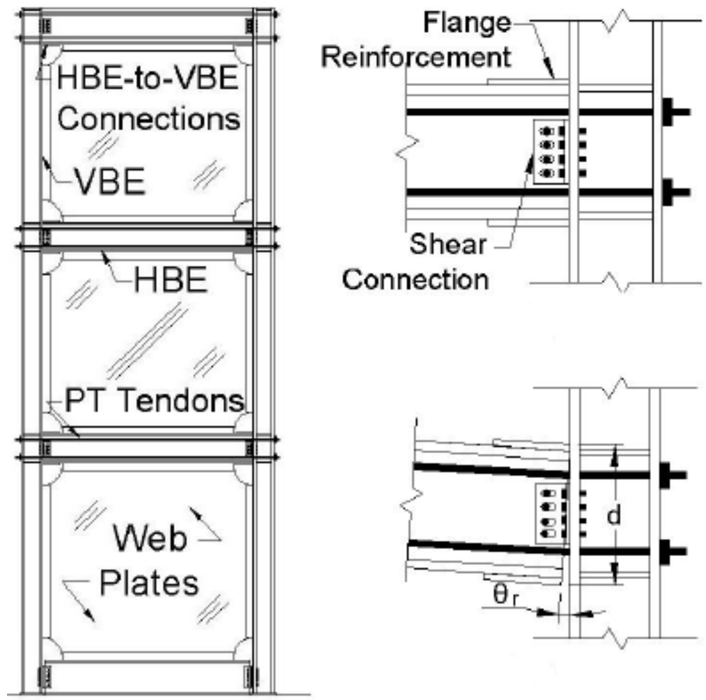


Figure 88 Elevation of SC-SPSW and PT Connections [after Clayton et al. 2011]

6.16. Takeuchi, T., 2011

"Seismic Design of Recent Projects on Tokyo Tech O-okayama Campus"

Introduction:

This paper presents case studies of structures using energy-dissipating and self-centering systems: the new library building and the secretariat building retrofit on Tokyo Tech's O-okayama campus. These structures were designed to withstand level-2 earthquakes with a maximum acceleration response of 1000cm/sec^2 at their elastic limit and they were expected to be usable after such an earthquake. The structural systems of the buildings are modeled analytically to see that they can withstand an earthquake.

System Concept:

The New Library: The old library at Tokyo Tech was insufficient for withstanding seismic forces. The building could not adopt retrofit designs because of deterioration of the concrete materials. The authors proposed an underground library, which maintained an unobstructed view along the axis from the main gate to the main building and kept valuable documents away from sunlight. An above-ground building was added to this design, named the Glass House.

The Glass House is composed of three triangular stories. V-shaped diagonal columns support each story. Perimeter frames are composed of perimeter beams and plate columns at the second and third floors and form a vierendeel truss. The toe of the plan is a 15 m cantilever and is supported by a pair of diagonal columns. The EV shaft, composed of truss frames with concrete walls, receives about 50% of the horizontal force.

The Secretariat Building: The Secretariat Building is located on the O-okayama campus. Its seismic performance was judged to be insufficient, and it was decided that retrofit was necessary. In order to reinforce the longitudinal frames, additional concrete walls or braces along the windows of office blocks and between the front pilotis columns were considered. However, this concept had some problems. Designers wanted to avoid additional braces between the front columns since they could change the appearance of the building. Moreover, in the office floors, the spaces between the columns were occupied by various facilities; therefore additional braces between the columns were not desirable; and concrete walls that block the windows were not acceptable.

An integrated façade concept was applied. This concept aims to design a new façade that can improve the architectural features, the seismic performance, and the energy efficiency of the building. This façade was composed of seismic energy-dissipating braces, horizontal louvers and glass. The authors also developed diagonal energy-dissipating louvers with the diagonal parallel louvers acting as buckling-restrained braces. These hysteretic dampers are used as energy dissipation braces. They are also effective at controlling sun light.

Seismic Performance of the Structure:

The New Library: To analyze the dynamic characteristics of the new library, eigenvalue analyses were carried out; and the seismic performance of the structure was evaluated by a time-history analysis. The first mode of the structure was found to be a twisting mode. The second mode dominated the vibration in the y direction, and third mode in the x direction. The fourth mode primarily consisted of vibration of the vierendeel truss in z direction. All these vibration modes had similar natural periods, and the seismic response of this structure was expected to include a combination of these modes. Analysis results show that members did not exceed their ultimate limits, and thus the structure remained within its elastic limit.

The Secretariat Building: The retrofitted structure could generally withstand an earthquake with a response of 1000cm/sec^2 up to the elastic limit of the existing frames.

Representative Figure of the Structure:

Figure 89 The New Library Building and The Secretariat Building [after Takeuchi et al. 2011]

6.17. Ozaki, F., Kawai, Y., Kanno, R., and Hanya, K., 2013

"Damage-Control Systems Using Replaceable Energy-Dissipating Steel Fuses for Cold-Formed Steel Structures: Seismic Behavior by Shake Table Tests"

Introduction:

A damage-controlled system consists of energy dissipating devices, controlled rocking, and self-centering capabilities for advanced seismic performance. These systems minimize damage to both structural members and interior/exterior finished. The proposed system contains small-size hold-downs, with a built-in fuse function (HDFs), which are to be placed in the foundation of a multistory shear wall. Through analytical analysis the HDFs were shown to have excellent seismic resistance when compared to ordinary shear walls. This paper presents the experimental testing of full scale specimens and the resulting conclusions.

System Concept:

The HDF is designed for multistory shear walls for cold-formed steel frames. The fuse element dissipates energy through a yielding steel plate. The butterfly pattern of the steel plate allows maximum energy dissipation capacity through simultaneous yielding over the full cross section of the fuse. Advantages of the steel fuse over the viscoelastic fuse is the hysteresis curve of steel is less dependent on strain velocity during earthquake motion and the yield strength and elastic stiffness of the fuse can easily be controlled by changings its geometry. The HDF assembly consists of a pair of fuse steel plates slot-welded to a U-shaped steel channel which is placed between the rocking frame and the foundation. The self-centering force is provided by the vertical gravity load.

Experimental Study, Results and Discussion:

A 1-story single span full scale steel sheet shear wall specimen was subjected to shaking table test. Four type of connection details were examined: a specimen with HDFs and a yield strength of 5kN, one with HDFs and a yield strength of 10kN, one with elastic fasteners tightly connection column base to the foundation, and one without hold-downs allowing free column uplift. Input motions from the El Centro NS and the Japan Meteorological Agency Kobe-NS data records were simulated.

Shake table test showed that the HDFs provided good energy-dissipation capacity which reduced the base-shear and subdued the uplift deformation of the specimen. Residual deformations of around 0.5 mm were found when the HDFs were implemented. The free rocking condition specimens exhibited large uplift deformations and it is noted that this motions is very difficult to control when no overturning resistance is provided.

Representative Figure of the Structure:

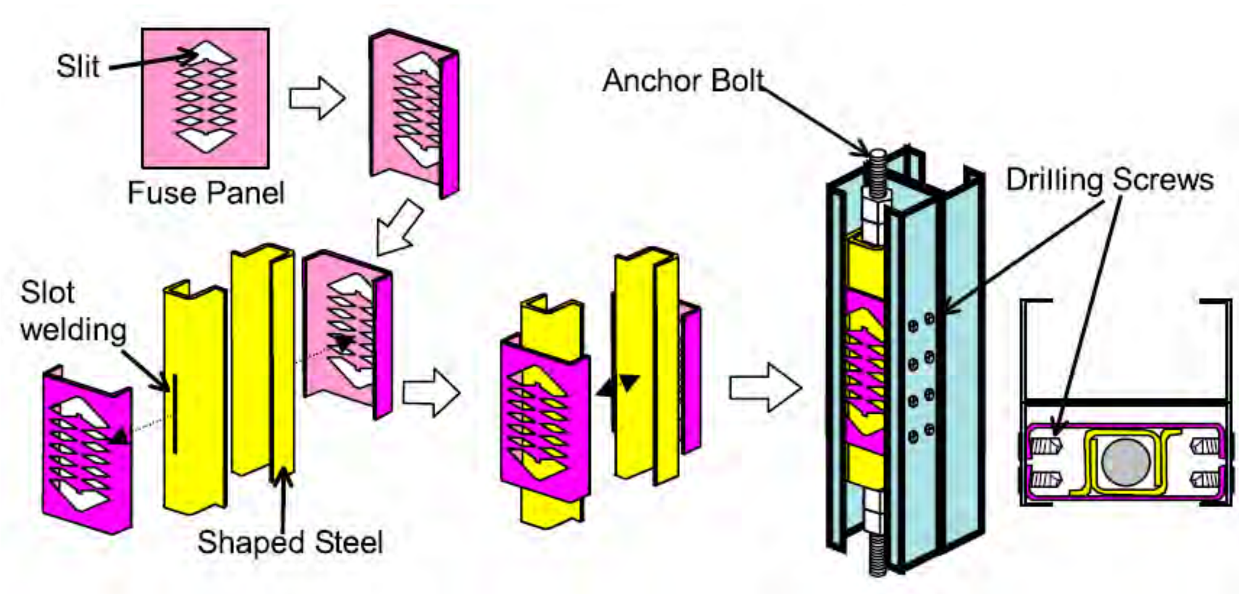
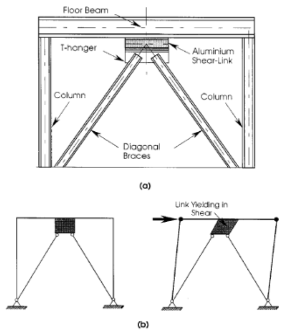
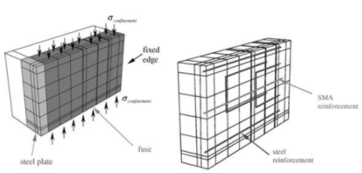


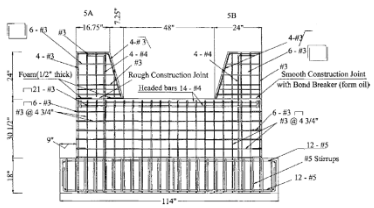
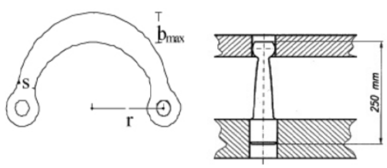
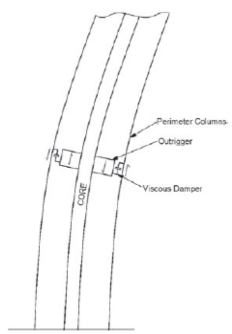
Figure 90 Hold-downs with a built-in fuse function (HDFs) [after Ozaki et al. 2013]

7. Tables of Literature Review

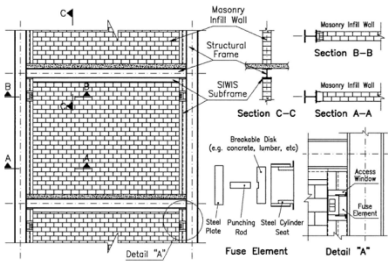
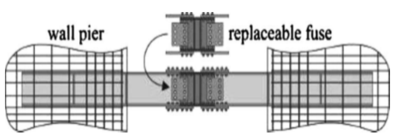
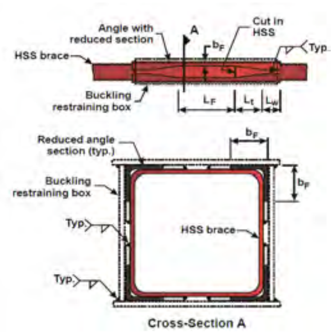
7.1. Table 1 Structures with Energy-Dissipating Fuses

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.1 Rai, 98'		An aluminium beam shear-link which yields in shear mode to limit maximum later force in earthquake resistant systems	I-shaped aluminium beam is place between the tops of the diagonal braces and a floor beam from the story above	The link was tested with varying parameters to determine energy dissipating capabilities and an analytical model was created to compare seismic performance to an ordinary CBF	Describe the inelastic cyclic behavior of the shear-link and its role as a seismic energy dissipater in a bracing frame structural system
2.2 Cristafulli, '03		Precast concrete walls with energy-dissipating embedded ductile perforated steel plates	Welded steel plate connections for precast concrete elements	Study behavior of isolated connecting plates, develop response design equations, and test reduced scale specimen with proposed connection detail	Investigate connections for precast concrete elements under seismic events for low to medium rise buildings
2.3 Krstulovic-Oparar 03'		Members combining conventional "passive" high-performance fiber reinforced concrete (HPFRCs) with "self-pre-stressing" shape memory alloy (SMAs)	Self-actuating composite members designed to adjust their load-displacement response to seismic excitations, provide energy absorbing zones, and be replaceable after an earthquake	Proposed design is evaluated using numerical simulation with plans of future detailed experimental investigations	Explore validity of "self-actuating" HPFRC fuse concept and determine whether sufficiently high increase in fuse response can be achieved

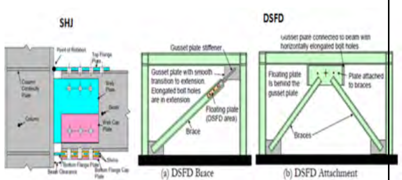
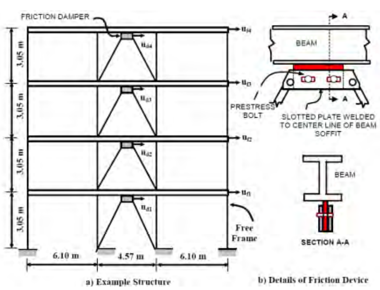
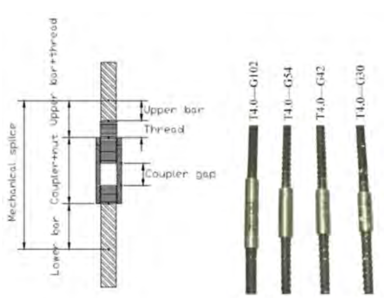
Article	Test/Analytical Setup	Test Load Description	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.1 Rai, 98'	1:4 scale models were created with varying section dimensions, two different alloys of aluminium (3003 and 6061), and arrangements of transverse stiffeners	Cyclic load tests were conducted with varying frequencies	Aluminium beam shear-links which dissipate energy through yielding in shear mode	Yes and retrofitting capabilities	No	The experimental testing showed the links ability to dissipate significant amounts of energy and the numerical results showed the shear-link braced frame had many seismic performance enhancements
2.2 Cristafulli, '03	Two stiff framed steel plates with two connecting perforated steel plates were mounted in a 250 kN screw driven INSTRON universal testing machine	Steel plates were tested under reverse cyclic shear forces and specimens was tested under cyclic lateral loading	Perforated steel plates with a width approximately 1.6 times the diameter of the hole (test specimen: 250 wide x 80 deep x 10 mm thick; 50 mm diameter hole)	No	No	Results show the design is adequate for shear in vertical joints, functions with excellent ductile displacement capacity without strength or stiffness degradation, and had advantages of simplicity over other proposed connecting devices with the same object
2.3 Krstulovic-Oparar 03'	HPFRC fuse zones were modeled based off SIMCON and implemented into FEM	The fuse was fixed along one side while the load was applied across a rigid steel plate on the opposite side	HPFRC fuse zones are positioned in areas of high ductility such as beam end zones	Yes, by means of bolted connections to adjacent members	No	The experimental SMA-HPFRC fuses demonstrate different structural response from conventional systems, but provided self-actuating concentrated energy absorptions zones which can be replaced

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.4 Bozorgzadeh 06'		Shear keys in bridge abutments designed to provide transverse support to bridge superstructure	Smooth construction joints at shear keys and minimizing the reinforcement between abutment and shear key allows dissipation of energy through sliding shear failure	10 Shear keys, in sets of 2 and having varying designs, were tested for their ability to reduce input force to abutment piles through means of sliding shear failure	Reevaluate design equations for estimating capacity of shear keys, provide data to develop an analytical model of shear key capacity, and detail reinforcement and construction joint surface preparation at the interface of shear key-stem wall
2.5 Iqbal 06'		Soft first story for multi-story structures with a seismic elastoplastic isolation system composed of Teflon-stainless steel sliding bearings and steel dampers assembled in a single device	Sliding bearings carry primarily vertical load and dissipate energy through friction, while steel dampers provide the majority of energy dissipation	No analytical or experimental studies were directly preformed	Present and review energy-dissipating systems with varying shapes and arrangements from previous research for feasibility
2.6 Smith 07'		Damped outriggers were inserted between perimeter columns and the ends of stiff outrigger elements cantilevering from the core as a new design philosophy for high-rise buildings	The damper provides energy dissipation across the structural discontinuity of the core-to-perimeter column outrigger system	A steady-state force response analysis was conducted as well as wind tunnel high-frequency force balance measures for the design example	Design procedures, approaches and an example for damped outriggers is presented for the design of high-rise buildings

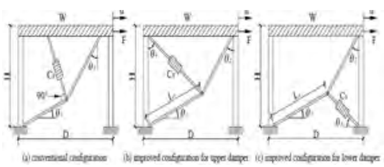
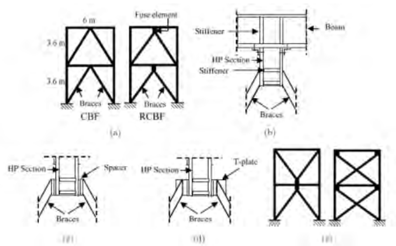
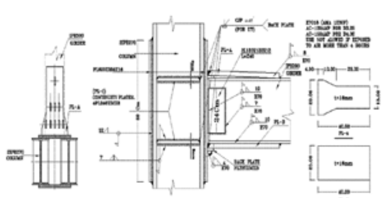
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.4 Bozorgzadeh 06'	Shear keys were built at 1:2.5 scale of a prototype abutment in a five series test designed to simulate exterior shear key-bridge superstructure interaction	Each key was loaded by two horizontal 980 kN compression capacity hydraulic actuators and displacement controlled cycles with increasing amplitude were run in three cycles	Shear keys designed with smooth construction joints and limited vertical reinforcement	No	No	An analytical model was developed to assist in designing the appropriate vertical reinforcement to induce sliding shear failure and a series of construction guidelines were created
2.5 Iqbal 06'	A variety of research on previous fuse design is discussed	-	Three primary discussed fuses: E-shaped, crescent moon-shaped, or with pin elements	Yes, with jacking of the first floor and reentering of building	No	The author concluded with well-established and proven isolation technology available, concepts for a soft first story with elastoplastic isolation system are feasible
2.6 Smith 07'	Direct analytical solutions obtained from 'complex modal analysis' and 'harmonic forced response analysis' and wind tunnel processing was performed for a 400m high tower	Analytical response measured Displacement vs. Frequency and wind tunnel processing measured Peak Acceleration and Overturning Moment vs. Period of Oscillation	Damping system described principally to reduce dynamic wind-induced response, but may be suitable for seismic response after appropriate non-linear history analyses	No	No	The described design procedure for a damping outrigger system has economic advantages, provides increased damping and stiffness, and results in a favorable response to cyclic motion

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.7 Aliaari 07’		Seismic infill wall isolator subframe (SIWIS) system used to prevent damage to columns or infill walls due to a sacrificial structural fuse	The steel frame with brick masonry infill walls was designed with pinned beam-to-column and column-to-column connections	In-plane lateral load testing of a scaled (1:4) 2-bay 3-story steel frame and a series of component tests on three different fuse element designs were performed	Experimentally test the potential of the SIWIS system for the development of an effective way to reduce earthquake damage in framed buildings with infill walls
2.8 Fortney 07’		Wall pier-coupling beam subassembly fitted with a steel coupling beam (SCB) and a SCB with an additional feature consisting of a central fuse system labeled as a fuse coupling beam (FCB)	Outer beam sections are embedded in the wall piers using same design as a typical SCB and an energy-dissipating fuse connection is located at the central beam connection	Full scale tested on SCB for low-rise steel buildings were performed	Enhance features of steel coupling beams by providing post-damage replacement capabilities without costly repair
2.9 Kassis 08’		Novel brace fuse system consisting of rectangular or square fuse systems for typical single story structures	Low-rise steel buildings and tall single story buildings	Brace slenderness on capacity design force is reviewed, a brace fuse system is proposed, results from specimen test are discussed, and results from a parametric study of system benefits are examined	A detailed braced fuse is presented and tested for its ability to reduce tension forces and maintain stable hysteretic response to seismic excitation

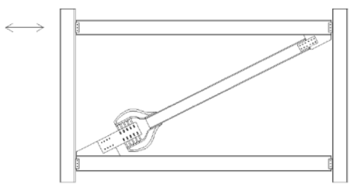
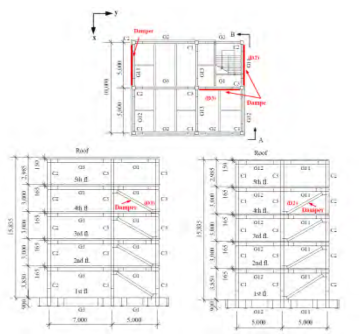
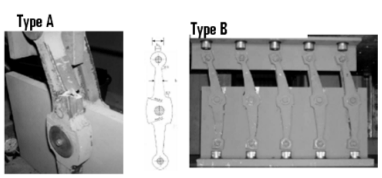
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.6 Aliaari 07'	Series of 11 tests; 4 tests on the bare fame, 5 tests on frame with fuse elements, and 2 test on pinned frame with fuse elements	Each test consisted of incrementally increasing displacements at the third floor level (displacement control)	A lumber disk element was selected over a concrete or steel disk due to it increased ductility and its slower load resistant deterioration rate	Yes, through specific small access window with the ability to replace the whole element as a component or an individual part	No	Experimental results show the SIWIS system works well as a seismic fuse system for infilled frames to save the infill walls from damage, but further experimental studies are needed to understand the system performance under cyclic loading
2.8 Fortney 07'	Coupling beams were embedded in wall piers and connected with a fuse system consisting of a slip critical web and flange splice connection	Specimens were loaded with sets of increasing amplitudes of reverse cyclic force or displacement followed by one cycle of decreased amplitude to capture stiffness degradation	Fuses are designed to have a shear capacity equal to the design shear with outer sections having sufficiently greater design shear to ensure they remain in the elastic range	Yes, through bolted connection	No	The FCB set up led to early energy dissipation and lower stiffness relative to the SCB and it is recommended the fuse be designed for ultimate shear forces in order to withstand expected shear forces
2.9 Kassis 08'	Single story steel building were laterally loaded at the roof level	Full-scale quasi-static cyclic and dynamic seismic frame testing	Fuse brace system consisting of structural tubing (rectangular or square) which is located near brace end	No	No	The proposed fuse design behaved with reduced tension forces and stable hysteretic response and it is noted marked strain hardening response was observed and must be considered in capacity design check

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.10 MacRae 08'		Sliding hinge joint (SHJ) located at connections and Double Surface Friction Dissipaters (DSFD) located within bracing	Steel moment frames with enhanced seismic performance	Paper reviews previous research performed on SHJ and DSFD systems	Provide consideration in the implementation of these energy-dissipating systems
2.11 Patro 08'		Analytical analysis of a 4-story frame building with friction devices	Multi-degree-of-freedom frame structure with friction slider mounted on the chevron brace	Analyze frame through two phases: non-sliding wherein the frictional resistance between floor and device has not been overcome and sliding or slip phase	Evaluate various dimensionless performance indices and optimal seismic performance of friction devices
2.12 Ruangrassamee 08'		Threaded mechanical splices which create a coupler designed to fail with sufficient energy dissipation	Connectors between pre-cast concrete members	Test coupler under varying parameters and loading conditions for energy dissipation performance	Investigate tensile, compressive, and cyclic behaviors of the developed threaded mechanical splices

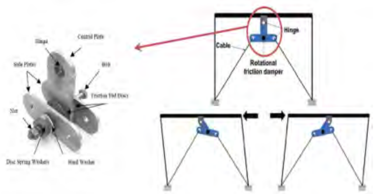
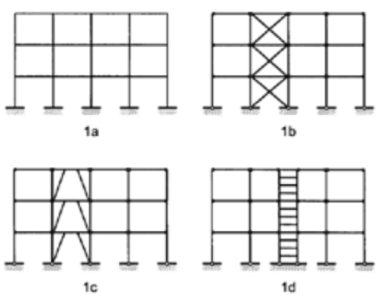
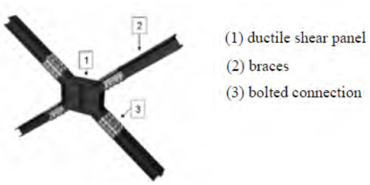
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.10 MacRae 08'	-	-	SHJ system- energy dissipation occurs in slip between beam and bottom flange plate; DSFD system-energy dissipated through bolted floating plate within braces	No, SHJ Yes, DSFD	No	SHJ connection provides adequate seismic performance and has been used in construction of NZ buildings and the DSFD provides advantages over ordinary BRB including no significant frame damage and are replaceable
2.11 Patro 08'	Linear behavior of the structure with friction devices is assumed and verified at both stick and sliding stage of response	Nine ground motions were recorded on different soil conditions and used to evaluate the frame	Friction energy-dissipation devices with slotted bolted connections, where the sliding plate within the vertical plane is connected to the centerline of the beam soffit	No	No	Behavior of actual friction is more complex than the typical designs based on Coulomb friction, realistic friction model may alter effectiveness of present practice, and optimum pre-stress force may be very different for different response quantities
2.12 Ruangrassamee 08'	Thickness and gap size were varying parameters under tensile test, compressive test, and cyclic test	Test were performed under the displacement control mode for monotonic tension testing and under two cycles per a specified max deformation for compressive and cyclic test	Composed of hollow steel coupler threaded throughout its length and two reinforcing bars with threads at their ends	Yes, repair at a connection will be simplified by replacing couplers	No	Load resistance is controlled by the coupler thickness while its ductility is controlled by gap lengths, splice exhibits higher resistance in compression after buckling, and energy dissipation increased in the cyclic test as the gap length increased

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.13 Bo 08'		Toggle-brace-damper (TBD) installation configuration with the damper directly connected to the beam-column joint	The TBD system provided energy dissipation for MRFs	Investigate magnification factor for damper displacement and force, and create expression for prediction of equivalent linear viscous damping ratio for TBD systems installed in a building	Present a simplified procedure for design and analysis of buildings incorporating the improved TBD systems
2.14 Dicleli 09'		Seismic retrofitted chevron-braced frame (RCBF) with a hysteretic energy-dissipating element installed between the braces and the connected beam	Chevron type retrofit bracing for a concentrically braced frame	The RCBF is presented and examined analytically and details of the retrofitting method are given	Validate proposed RCBF for energy-dissipating capabilities and compare to conventional CBF performance
2.15 Farrokhi '09		Cover plate type moment resisting connections with drilled holes	Steel MRF with reduced plate section in the beam to column connections	Test proposed moment resisting connections under cyclic nonlinear finite element analyses on numeric models and experimentally using full scale models	Propose effective solution to reduce stress concentration at the weld roots by means of reducing the section of the beam or the connector elements

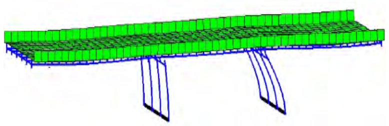
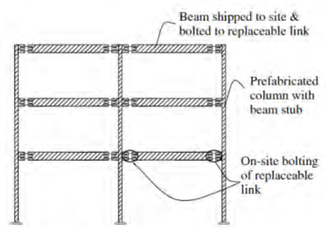
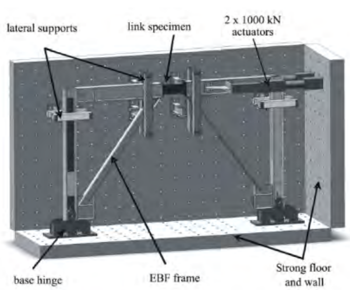
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.13 Bo 08'	Analytical model consisting of a 3-story, three span steel MRF	Three artificial acceleration time histories were generated using SIMQKE software and a response history analysis was analyzed	Viscous dampers	No	No	The proposed design method, based on philosophy of displacement-based seismic design, is simple yet effective for use in rapid design and analysis of structures with TBD systems
2.14 Dicleli 09'	Single story frames and multistory frames (2 and 4) nonlinear static pushover, time-history and damage analyses were conducted	A set of seven scaled ground motions were simulated	HP section, which is composed of stocky plates capable of undergoing large inelastic lateral deformations; retrofitting requires cutting braces from gusset plate and attaching fuse	Yes	No	RCBF exhibits a more stable and desirable lateral force-displacement relationship, a more stable behavior over a wide range of structural and ground motion properties, and less damage and larger reserve lateral deformation capacity compared with the CBF
2.15 Farrokhi 09'	Three full scale models were fabricated using a T connection with the column aligned horizontally and mounted on a reaction frame	A saw tooth load pattern was implemented to account for the cyclic degradation phenomena	Cover plates with drilled holes	No	No	It was found the drilled holes shift the stress concentration from the connection face through the cover plates, and may eliminate the unfavorable brittle cracking mode of the weld roots and enhance the structural performance and reliability

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.16 Gray 10'		Cast steel yielding fuse (CSF) using inelastic flexural yielding of specially design yielding elements of the cast connector	Energy dissipation system for concentrically brace frames	The cast connector concept is introduced, the cast steel material used for a device prototype is discussed and finally full-scale proof-of concept laboratory test results are presented	Present the feasibility of a CSF device to eliminate the cyclic tensile yielding and inelastic compressive buckling of traditional braces
2.17 Kasai, 10;		Full scale experimental testing of a steel frame with varying dampers	5-Story steel MRF examined with a steel, oil, viscous, and viscoelastic damper system	Full scale shake table testing on the E-Defense table in Japan based on previous analytical modeling and damper component test	Validate the reliability of the passive control technology through realistic experiments and compare to MRF without damping system
2.18 Chen 11'		A three-pin steel damper is designed for energy dissipation through damping rather than inelastic behavior of primary structural members	Damper can be installed on a separated wall within a panel in a steel MRF	The damper unit was tested for strength and displacement and an analytical model was created based on the results	Evaluate if the proposed damping system is a feasible alternative for seismic resisting systems

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.16 Gray 10'	Full scale prototype was designed, manufactured and tested under axial stress representative of the stiffness of a buckling restrained brace	A cyclic, quasi-static axial loading was induced with a universal testing machine	Ductility of the yielding element is maximized by shaping the fingers to induce flexural yielding along most of their length	No	No	Experimental results of an axial test of the CSF-brace assembly prototype confirmed the expected stiffness and ductility response of the device which closely matched analytical predictions
2.17 Kasai, 10;	Full scale tested was conducted on the E-Defense Table of a 5-story steel MRF	Excitations simulated were a DBE, maximum considered earthquake acceleration, the JR Takatori Ground Motions, and a 5% Damping Ratio.	Four dampers were considered: steel, oil, viscous, and viscoelastic	Yes	No	The dampers provided significant energy dissipation, the buildings showed significantly less peak responses, and the story drift angle was within the 1% design target value
2.18 Chen 11'	A model of a 14-story R/C building with the dampers was created using SAP2000	Displacement controlled cyclic tests were conducted on the damper	Three-pin steel dampers are always in pairs and connected using pins providing easy manufacturing and avoidance of weld quality issues	Yes	No	The three-pin damper exhibited stable behavior with large hysteretic loops and the analytical model showed the damper provided an effective reduction in seismic response

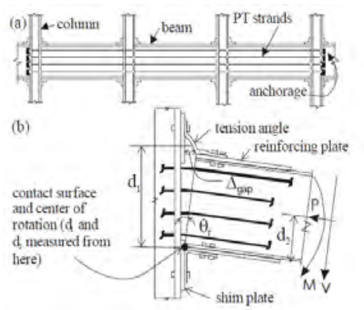
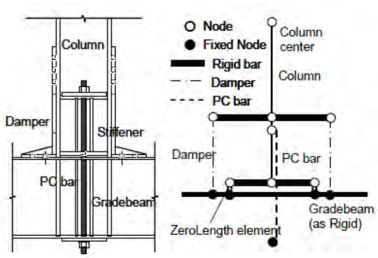
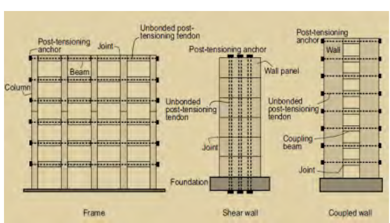
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
2.19 Kim 11'		Rotational friction dampers connected to high strength tendons to enhance both seismic and progressive collapse-resisting capacity of existing structures	Seismic retrofit of mid to high level rise reinforced concrete moment frames	Present the performance of fiction dampers connected to high strength tendons and numerically analyze 3,6 and 15-story reinforced concrete moment frames fitted with dampers	Evaluate the performance of the proposed energy dissipation system against seismic loads and their seismic and progressive collapse resisting capacity
2.20 Karydakis 11'		The Innovative Stiffness and Energy Dissipation System (INSTED) is composed of two vertical strong columns, which remain elastic, and expandable horizontal connections for energy dissipation through plastic hinging	Anti-diagonal bracing in MRFs are replaced by vertical composite beams composed of two strong columns of square hollow section which are joined by horizontal beams in a tight arrangement	Several test were run on varying connecting elements for their capability to dissipate energy and an analytical model was developed to compare the results; also the final design proposal was detailed	The paper presents continuing work on the INSTED system with goal of providing experimental and analytical conformation of the seismic energy dissipation abilities for multi-story MRF buildings
2.21 Valente 11'		The Braced Ductile Shear Panel (BDSP) system provides energy dissipation through four concentric X-braces in series with a yielding rectangular ductile shear panel	The bracing system is designed to be used as a retrofit or within new design for MRF and concentrically braced frames	A model was created to evaluate the BDSP system behavior and a frame model was developed for global system evaluation	Assess the effects of the BDSP system as a retrofit measure and analyze the behavior of the system analytically under seismic loading

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.19 Kim 11'	Analytical models, consisting of 3,6 and 15-story reinforced concrete moment frames designed as ordinary MRFs and Special MRFs, were modeled using OpenSees	An artificial earthquake with peak ground acceleration equal to 0.5 g was generated	Composed of a central steel plate, two side plates and two circular friction pad discs placed in between the steel plates, which is all attached to an inverted pretension V-brace	Yes and able to be retrofitted in structure	No	Nonlinear dynamic time-history analysis results showed that the structures retrofitted with rotational friction dampers generally satisfy the given performance objectives against seismic load
2.20 Karydakis 11'	15 full scale test were performed using three groups of connecting beam elements: beams of similar section, bars and rods, and beams of variable cross sections	The elements were tested under cyclic loading	The fuse element is created by expandable horizontal connections where plastic hinges are formed	Yes	No	The system exhibited energy dissipation abilities and the experimental results were backed up by analytical numerical results from finite element analysis
2.21 Valente 11'	An finite element model of the brace was developed using ABAQUS and an analytical model of a 6-story steel frame was developed using SAP2000	Fully reversed displacement cycles were applied the analytical model of the system and a nonlinear dynamic analysis was used to evaluate the analytical frame model	Ductile shear panel composed of non-slender in-plane plate elements and stiffened by boundary flanges	Yes	No	The study provided a global analysis for the BDSP system which decreased maximum top displacements in the frame and reduced plastic demands of the structural elements under seismic activity

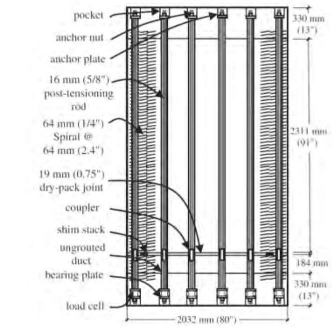
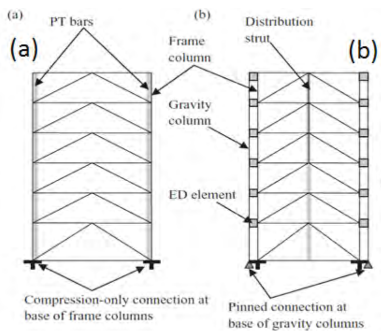
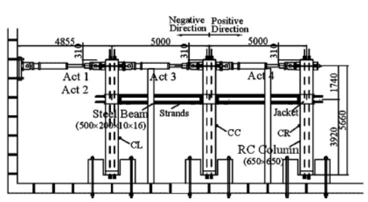
Author	**Representative Figure**	**Description of System**	**Frame Configuration**	**Experiment Synopsis**	**Purpose of Research**
2.22 Filipov 11'		Bridge system employing quasi-isolation by using a set of fixed bearings in addition to isolation bearings	System uses stiffened L-shaped retainer brackets that limit transverse displacement of elastomeric bearings, so that the bridge responds elastically under service loading with certain bridge bearing components fusing under large seismic events	A computational system analyses is performed for the described bridge system as well as modeling of the nonlinear behaviors of the substructure pier elements, bridge foundations and abutment back walls	A parametric study of the conceptual model is being investigated for various bridge structures and bearing combinations to develop further design strategies
2.23 Shen 11'		Nonlinear replaceable link concept allowing a location of expected decoupled inelastic action	Steel MRF with nonlinear replaceable links located away from the beam-column connection	Full-scale testing of two different replaceable link connections is examined and an finite-element model is developed for comparison of behavior	Experimentally validate the behavior of a nonlinear replaceable links as an alternative to traditional MRF beam-column connections
2.24 Mansour 11'		Eccentrically Brace Frame configuration with ductile replaceable shear links which are decoupled from the structural members	Replaceable links located within floor beams, between eccentric braces for a steel frame	Component test on two types of links and full scale global performance of the new EBF assembly were conducted and examined	Assess an alternative to conventional EBF with a replaceable shear link providing advanced seismic performance, economic advantages, and extended building life - span

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
2.22 Filipov 11'	An analytical model was created in OpenSees and incorporates linear elastic behavior for all elements	Varying superstructure and substructures were modeled using several suites and intensities of ground motions	L shaped retainers designed as fuse components to fracture the attached anchor bolt under seismic motion	Potentially, more research needed	No	Initial results show bearing friction force has a large influence on the superstructure displacement in the transverse direction and the abutment back wall tends to limit longitudinal displacements
2.23 Shen 11'	Four full-scale assembly tests were performed on the beam-column assembly with replaceable links representing a first floor exterior connection	Cyclic loading test were conducted until specimen limitations	W-sections with endplates connections and back-to-back channels with bolted web connections	Yes	No	MRF with nonlinear replaceable links provided adequate strength and ductility and end-plate links showed greater energy dissipation capacity than the bolted web links
2.24 Mansour 11'	Component test for ductility capacity and full scale testing of the first story EBF assembly of a 5-story EBF were conducted	Link specimens were tested in shear and reverse moment curvature, and the full scale assembly was tested under cyclic shear deformations	First link was a W-section welded to unstiffened end plates and the second was two channel sections back-to-back with a welded or bolted connection	Yes	No	The link specimens were all found to achieve at least 0.08 rad plastic link rotation and the EBF with shear links was shown to transfer 14% more shear than the bare steel link and maintain the ability to be replaced with as much as 0.05% drift

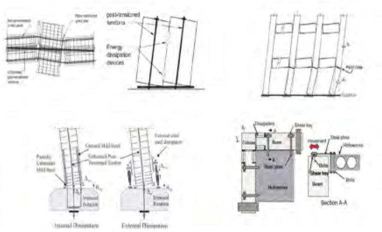
7.2. Table 2 Structures with Self-Centering

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
3.1 Garlock 06'		Bolted top-and-set angles are used with high strength 7-wire strands running parallel to beam and anchored outside the connection	Self-centering moment resisting frame (SC-MRF) designed for earthquake-resistance	Analytically evaluate the effects of the floor diaphragm stiffness, strength and configuration of the system in response to seismic events	Analyze proposed prototype capability to reduce or eliminate structural damage and return to its original position
3.2 Ikenaga 06'		A self-centering column base is presented using a PC bar and steel damper to suppress residual deformations	Column connection for steel frame	An analytical analysis of the connection detail was performed	Analyze the column connection for self-centering capabilities and system behavior
3.3 Walsh 08'		Behavior analysis of single strand/anchorage systems	Unbonded post-tensioned structures	Investigate strand size, anchor type, number of anchor wedges and presence of a binding ring around wedges	Evaluate strand/anchor configurations that may provide better probability of reaching higher stand ductility

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
3.1 Garlock 06'	A prototype building, 6-story 6-bay steel frame is modeled in DRAIN-2DX with varying floor diaphragm characteristics	The model was subjected to nonlinear time-history analysis using six varying ground motions (each one scaled to two levels)	-	-	Yes, through anchored post-tensioned strands running parallel to beam	Larger collector beam stiffness results in smaller relative displacements between the SC-MRF and the floor system, and also creates larger axial forces, moments, and strains in the SC-MRF beams
3.2 Ikenaga 06'	-	A static pushover and dynamic analysis were conducted	-	-	Yes, through PC bar in the connection	The system exhibited stable behavior for both positive and negative deformation and several repetitions and the stiffness and moment from the dynamic analysis were similar to those predicted by the static analysis
3.3 Walsh 08'	Each strand specimen was positioned through the crossheads of the testing machine, with a PT anchor placed on the outer surface	Specimens were each run through monotonic tension tests	-	-	Yes, through unbounded post-tensioned strand systems	Results show that maximum stress and strain capacity of the strands is controlled by the fracture of individual strand wire(s) inside the anchor wedges

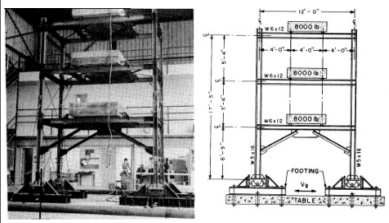
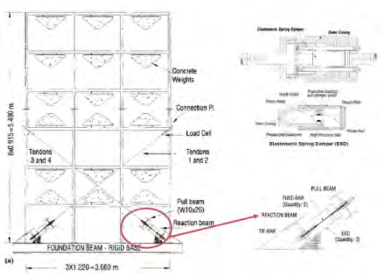
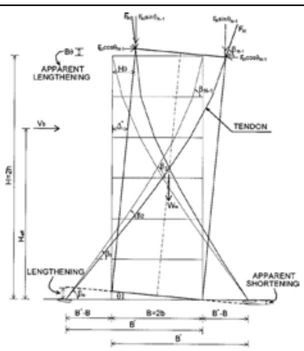
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
3.4 Erkmen 09'		Unbonded post tensioning is used for self-centering capabilities in concrete shear walls	Precast concrete shear walls	Experimental testing of the PT force in concrete shear walls is conducted and an analytical model is developed to examine PT configuration	Analyze the behavior of concrete shear walls experimentally and analytically
3.5 Roke 09'		Frame with lateral load behavior causing column rocking on its base and vertically-aligned post-tensioned bars resisting uplift and providing restoring force	Self-centering concentrically-braced frames (SC-CBF)	Present analysis results from several SC-CBF configuration using probability-based design methodology to determine member force design demands	Use dynamic analysis to confirm drift capacity and self-centering behavior of proposed systems and nonlinear time-history analysis to validate design methodology
3.6 Chou, 09'		PT self-centering frame with gap-openings at beam-to-column interfaces	PT RC columns with PT beams	Validate a 3-story analytical model through full scale experimental testing	Provide a more accurate model of PT frames by evaluating bending stiffness of column and compression forces in the beams based on a deformed column space which matches the gap-opening

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
3.4 Erkmen 09'	Specimens were tested for their ability to self-center throughout repeated loading	Cyclic loading was applied	-	-	Yes, through PT tendons and self-weight	Initial PT force did not have a significant impact on SC, nor did the placement location of the PT
3.5 Roke 09'	OpenSees was used to model several 6-story SC-CBF systems using pushover analysis to simulate earthquake loading	A suit of 12 DBE-level ground motions were used in the analysis	-	-	Yes, the system uses PT bars to resist rocking and column uplift and to self-center	Dynamic analysis results show that design demands safely account for higher mode demands through probability-based methodology and higher modes contribute to the response during rocking which results in an increase in the member forces
3.6 Chou, 09'	Full scale experimental testing of the substructure of a 3-story frame	A quasi-static cyclic loading was implemented through a series of actuators	-	-	Yes, through vertical and horizontal PT	The analytical model procedure was validated by the experimental results, and showed earlier analysis methods were over conservative

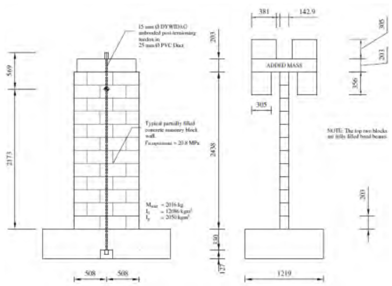
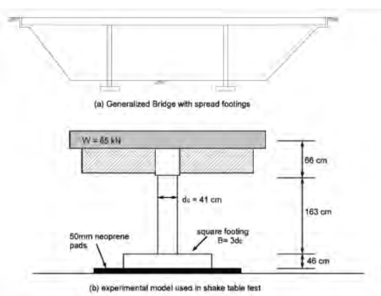
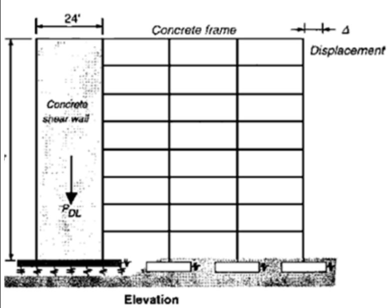
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
3.7 Pmpanin 10'		Energy dissipation seismic systems in recent times are reviewed	Systems reviewed: (1) joined ductile articulated systems, (2) replaceable fuses, (3) articulated floor systems and (4) Pres-Lame Systems	Author provides on-site applications and case studies	Provide information regarding recent developments and emerging solutions for seismic performance and damage control based on traditional materials and available technology
-	-	-	-	-	-
-	-	-	-	-	-

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
3.7 Pmpanin 10'	-	-	-	-	-	An overview is given of recent seismic performance systems and a look into the implementation of these systems is provided
-	-	-	-	-	-	-
-	-	-	-	-	-	-

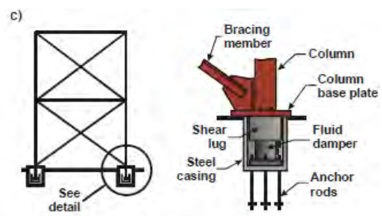
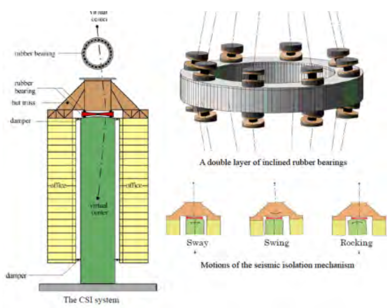
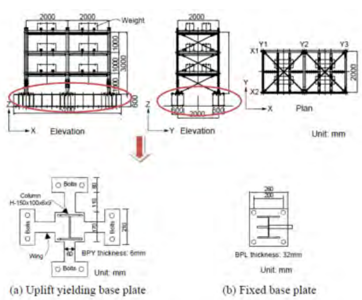
7.3. Table 3 Structures with Rocking and Energy-Dissipating Fuses

Author	**Representative Figure**	**Description of System**	**Frame Configuration**	**Experiment Synopsis**	**Purpose of Research**
4.1 Hucklebridge 77'		Steel frame allowing column uplift in response to severe seismic loading	Steel MRF with capability to rock about base for energy dissipation	Analytically and experimentally examine frame column uplift	Provide analytical correlation of experimental rocking frame and an analytical model
4.2 Pekcn 00'		A load-balancing tendon fuse + damper (TFD) system provides a supplemental damping system with fuse elements	Moment frames consisting of sacrificial yielding fuse-bars and elastomeric spring dampers (ESD) for seismic response mitigation	An experimental and analytical study is presented that investigates the effectiveness of the proposed system under seismic activity	Verify an improved velocity-dependent computation model and compare varying test model configurations performances
4.3 Ajrab 04'		Rocking wall-frame building with various supplemental system configurations including prestressed tendons and energy dissipation devices	Rocking walls coupled with a separate non-load bearing nonlinear supplemental damping system	Evaluate system damping, propose stages involved in designing supplemental systems, and provide a design example and performance evaluation	Introduce the implementation of the proposed system on a performance-based design methodology

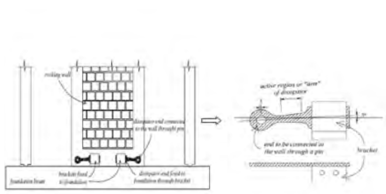
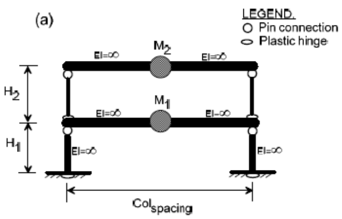
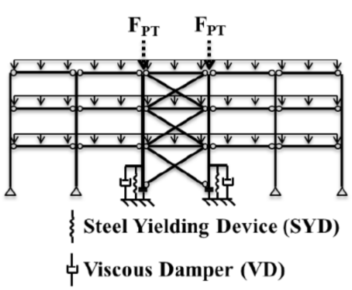
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
4.1 Hucklebridge 77'	3-story single bay steel moment frame	Shake table test were used to perform earthquake simulation	-	-	No	It was found that column uplift resulted in a definite reduction in structural force response quantities
4.2 Pekcn 00'	Model structure is ¼ scale, 3-story MRF; 7 test configuration were utilized	Three different ground motions with various peak ground acceleration levels were simulated on a shake-table	ESD contain silicone-based elastomer providing spring and hysteretic behavior; and fuse bars consisting of high strength threaded rods	Yes, fuse bars can be removed and replaced	No	ESD devices were effective in reducing overall seismic response, initial peak response due to pulse-type input motion were controlled better by the load balancing TFD system, and fuse-bars were effective in reducing peak response
4.3 Ajrab 04'	6-story rocking wall-frame building analytical test model was designed using DRAIN-2DX	A series of nonlinear time-history analyses using varying ground motions were implemented	Energy dissipation system consist of various pre-stressed tendon configurations	Yes	No	It was found the rocking shear wall-frame system provided feasible alternative to fix-base counterpart

Author	**Representative Figure**	**Description of System**	**Frame Configuration**	**Experiment Synopsis**	**Purpose of Research**
4.4 Ma 06'		Controlled rocking walls for advanced seismic performance	Vertically PT masonry concrete walls	Experimental testing for rocking wall behavior data was compared to frequently used analytical analysis methods	Examine the discrepancies in actual dynamic behavior and response of controlled rocking walls to previous analysis methods
4.5 Mahin 06'		Simple inverted pendulum concrete bridge column with energy-dissipating rocking capabilities, reducing force demands on bridge	-	Analytical and experimental test were conducted for multidirectional earthquake performance evaluation of rocking bridge footings	Develop reliable analysis procedures for evaluating proposed bridge structure and validate through refined analyses and shake table test
4.6 Gajan 08'		Frame-shear wall structure supported by shallow foundations, where lateral loads during seismic loading are transferred from beams to shear wall to shallow foundation	Rigid steel or aluminum shear wall with footings able to rock about base	Series of centrifuge experiments were performed to study effects of footing dimensions, depth of embedment, and initial static vertical factor of safety on nonlinear soil-footing system responses	Validate the systems response in terms of load capacities, stiffness degradations, energy dissipation and permanent deformations beneath the footing

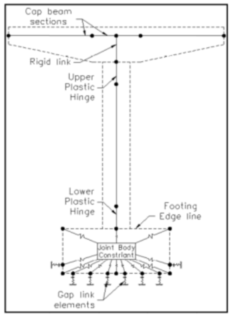
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
4.4 Ma 06'	Full scale shaking table testing was performed for a PCM wall	The wall was subjected to a scaled 94' Northridge EQ record	Vertical PT steel through material yielding	Repairable	No	The experimental data proved previous analysis methods of behavior prediction of controlled rocking concrete walls was inadequate and more research is needed
4.5 Mahin 06'	Simple reinforced concrete column and footing resting on 50 mm thick neoprene pad	Multidimensional shake take analysis	-	-	No	Initial results found displacement was similar or smaller than expected comparable elastic or yielding systems, column showed no signs of damage and re-centered following ground shaking
4.6 Gajan 08'	12 tests were conducted on varying shear wall-footing structures and foundation properties, implemented with an actuated and base shaking	Shallow foundations were subjected to slow lateral cyclic loadings and dynamic base shaking while out of plane movement was prevented by sliding Teflon supports	-	No	No	Rocking footings show very ductile behavior with negligible loss of capacity, significant energy dissipation capacity, and it includes a self-centering mechanism associated with uplift and gap closure upon unloading

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
4.7 Tremblay 08'		Viscously Damped Controlled Seismic Rocking (VDCSR), with column uplift resisted by column base dampers	Energy-dissipating system for chevron braced steel frames	A parametric study is conducted, and a design model is created and compared to experimental results	Evaluate the seismic performance of the VDCSR system
4.8 Nakamura 08,09'		Core-Suspended Isolation (CSI) system consisting of a reinforced concrete core on top of which sits a seismic isolation mechanism composed of a double layer of inclined rubber bearings	CSI system creates a pendulum isolation mechanism with a multi-level structure suspended from a hat-truss or umbrella girder system constructed off of it	CSI system mechanics are described, results of shake table test are presented and the first building constructed utilizing the CSI system is examined	Attain the highest possible level of earthquake resistance along with an architecturally desirable form in a structural system
4.9 Midorikawa 08, 09'		Steel frame with rocking response through column base-plate deformations	Conventional steel braced frame with yielding base plates allowing energy dissipation through rocking	Seismic response of scaled model with columns allowed to uplift is evaluated and compared to fixed-base frames and inelastic three-dimensional behavior of base-plate-yielding is tested and discussed	Improve understanding of seismic rocking response of structures subjected to strong earthquake motions and validate feasibility of designing steel frames to enable the rocking response through column base-plate deformation

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
4.7 Tremblay 08'	½ scale 2-story prototype model was tested using a multi-cellular shake table	Three ground motions were simulated and the frame was subjected to harmonic signals with various amplitudes and frequencies	Energy dissipation is provided by column base fluid dampers	Yes	No	All of the test specimens were able to sustain design ground motion demands without structural damage and experimental testing confirmed numerical model predictions of system behavior
4.8 Nakamura 08,09'	A suspended structure consisting of six concrete cubes hanging from top beam constructed over seismic isolation mechanism, was tested on a shake table	Shake table tests were performed to simulate scaled peak ground accelerations of recorded earthquakes and quasi-static loading test were performed on the rubber bearings	-	-	Yes, through practical pendulum isolation mechanism	It was found the CSI system elongates natural periods of structure which is not a design parameter available for conventional seismic isolation systems and a 4-level building utilizing the CSI system was constructed in Tokyo, Japan
4.9 Midorikawa 08, 09'	1/3 scale 3-story, 2x1 braced steel frames were tested on a shake table with two base condition; base-plate yielding uplift-base and fixed-base	Models were vibrated under scaled 1995 JMA Kobe earthquake simulation	Column base plate yielding provided energy dissipation	-	No	Max base shears are effectively reduced, rocking response displacements are nearly equal to or smaller than the elastic response of a fixed-base frames, and max tensile forces are limited to a relatively constant value less than fix-base frames

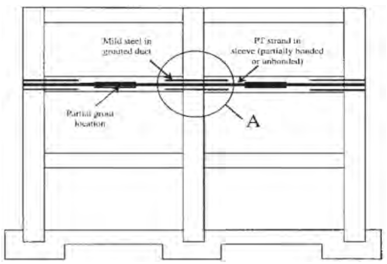
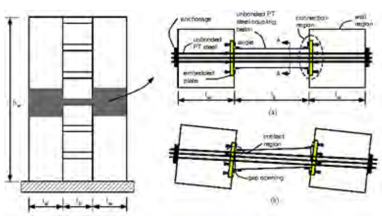
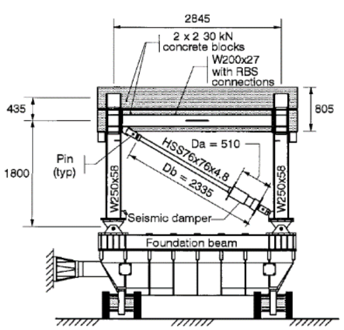
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
4.9 Toranzo 09'		Rocking masonry frame-wall system with energy-dissipating dampers	Confined-masonry rocking walls	System behavior and mechanisms are outlined and experimental results are discussed	Validate the concept of rocking walls as primary seismic systems
4.11 Liu 12'		Structural hinging-dominated (SHD) system is designed such that the strength to mobilize nonlinear rocking of the footing is larger than the yield strength of the fuse, where foundation rocking-dominated (FRD) is the opposite	Test model represents a moment-resisting frame founded on shallow footings	Present design and preliminary experimental results for two structural configurations and compare in terms of time-history and hysteretic response of structural elements and scatter plots for select engineering demand parameters	Experimentally evaluate the seismic behavior of low-rise frame buildings, considering two different yielding mechanism in the building system
4.12 Pollino 12'		The controlled rocking braced frame (CRBF) are designed such that the primary structural components remain elastic while passive energy-dissipating devices are implemented to control the response	Elastic braced frame within a building which is allowed to uplift from its supports prior to brace yielding and buckling with displacement-based steel yielding devices and velocity dependent viscous dampers	Behavior and design of a CRBF building including primary rocking mode and higher mode response are discussed and a nonlinear transient analysis is performed	Analytically evaluate controlled rocking brace frame seismic lateral force resisting systems for seismic performance

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
4.10 Toranzo 09'	2/5 scale 3-story prototype model frame was tested using a shake table	Five historical ground motions were chosen and six dynamic test were run	Pair of supplemental hysteretic energy-dissipating dampers at the base of the wall	No	No	Damage was eliminated from the system and it showed re-centering ability following the seismic simulation
4.11 Liu 12'	Two experimental models were tested in a 9-m-radius centrifuge-based shake table	Each test consisted of a similar sequence of five different motions from recorded earthquakes	Fuse element was achieved by weakening a hollow two section, via a notch	No	No	SHD system is more prone to localize at the fuse, with relatively little energy transfer to rocking causing significant transient and residual deformation in the model, where the FRD system minimized roof drift while fuse elements remained linear-elastic
4.12 Pollino 12'	Prototype 3-story building was examined using a nonlinear transient seismic analysis in the program ANSYS	A set of 10 ground motions from Los Angeles DBE bin of motions were used in the analyses	-	-	Potentially with PT strands	CRBF system can potentially provide increased seismic performance, and increased resiliency and sustainability of building structures

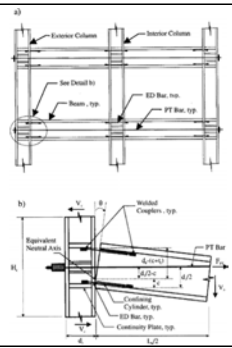
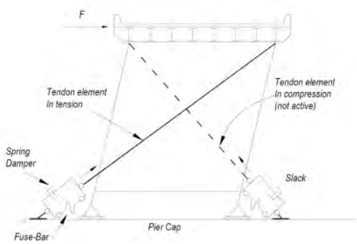
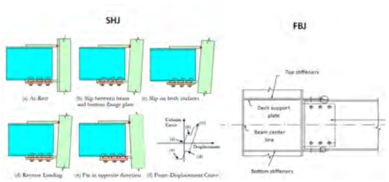
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
4.13 Saad 12'		Curved bridges with rocking foundations	Varying bridge curvatures with single column bents	Analyze seismic performance for complete bridge systems with rocking foundations and compare to systems without rocking through analytical and experimental models	Provide verification of rocking behavior ability to reduce the effect of earthquakes on bridges as system, not only on the bents
-	-	-	-	-	-
-	-	-	-	-	-

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
4.13 Saad 12'	Five bridges were modeled using SAP2000 with varying curvatures for the parametric study and a 2/5 scale model is under construction	Nonlinear time-history analyses were based on Northridge earthquake record at Sylmar station	-	-	No	Preliminary results indicate that horizontal curvatures in the bridges can have an impact on the distribution of forces in the system when rocking occurs
-	-	-	-	-	-	-
-	-	-	-	-	-	-

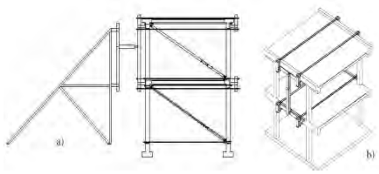
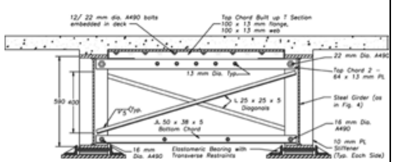
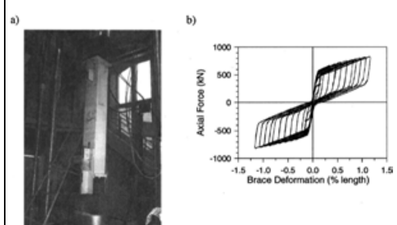
7.4. Table 4 Structures with Self-Centering and Energy-Dissipating Fuses

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.1 Shutt 97'		Hybrid frame with standard reinforcing steel and high-strength, post-tensioning steel cables at connection of precast columns and beams	Precast concrete moment frame that absorbs seismic energy	-	Previous research has provided an applicable design with advantages including decreased life-cycle cost, simplicity in design, reduced installation time and resiliency providing a safe structure
5.2 Kurama 00'		Coupled concrete walls using steel beams and unbounded post-tensioning, without embedding the beams into the walls	Unbonded post-tensioned hybrid coupled walls with flange cover plates to delay yielding of the beams and top and bottom seat angles used to provided energy dissipation	Develop an analytical model to investigate the behavior of the system under earthquakes and provide design and analysis of coupling beams	Provide preliminary analytical studies for future prototype coupled wall buildings
5.3 Filiatrault 00'		Energy dissipating self-centering friction spring damper for braced MRF	Steel MRF with damper retrofit	Characteristic test of the friction spring damper were conducted and a MRF braced with the damper was subjected to simulated ground motions for seismic evaluations	Evaluate the performance of a 200-kN capacity prototype of the damping system under simulated EQ ground motions

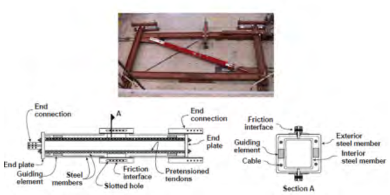
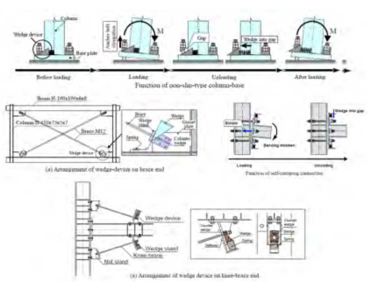
Article	**Test/Analytical Setup**	**Test Load Conditions**	**Description of Fuse(s)**	**Replaceable**	**Self-Centering System**	**Conclusions**
5.1 Shutt 97'	-	-	Mild steel and PT used across the joints	No	Yes, through precast horizontal orientated PT	Elastic response of the column and beam elements was shown through negligible cracks occurring under high levels of seismic excitation, which closed upon removal of the load
5.2 Kurama 00'	6-story analytical model was developed using DRAIN-2DX software	A nonlinear static and nonlinear dynamic time-history analyses were conducted	Inelastic energy dissipation is provided by top and bottom seat angles at the beam-to-wall connections	Yes	Yes, through high strength horizontal orientated PT	Analytical results show coupling in hybrid wall systems can be achieved by using unbounded post-tensioned beams without embedding the beams into the walls and can be done without causing significant damage in beams during later displacements of the walls
5.3 Filiatrault 00'	Half-scale shake table test were performed on a steel in plane MRF with and without the damping system	Frame was subjected to a push over analysis and four different ground motions from the 1940 El Centro record	Energy dissipation is provided by a friction spring damper which is to be located in the bracing of a MRF	Yes and possibilities of retrofitting existing buildings	Yes, damper displayed stable symmetrical hysteresis loops of force-displacement	Damping system provided sufficient energy dissipation and self-centering characteristics as well as reduced lateral displacements and accelerations

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.4 Christopoulos 02’		Post-tensioned energy-dissipating (PTED) connection for steel frames	Steel beam column connection consisting of high strength PT steel bars along with energy-dissipating bars	PTED connection is investigated analytically and experimentally through the development of an equivalent iterative sectional analysis and large-scale cyclic test	Provide further development of PT steel structures and validate seismic performed of the proposed connections
5.5 Pekcan 02’		Alternative seismic retrofit approach for end-sway frame of deck-truss bridges, consisting of modified bracing configurations including supplemental damping systems	Configurations include PT tension elements with fuse bar elements and spring dampers	Experimental and analytical investigations on a scale model of an existing steel end-sway frame are presented	Validate proposed retrofit configurations for improved lateral strength and stiffness, and test capability to modify load path to reduce overall structure demand
5.6 Clifton 03’		Flange Bolted Joints (FBJ) and Sliding Hinge Joints (SHJ) are designed to remain rigid up to ultimate limit state earthquake moment and then allowed to rotate at beam column connection	Moment-resisting steel frame with semi-rigid joints for seismic-resisting systems	Large-scale test of the FBJ and SHJ are analyzed and the behavior is discussed	The paper builds on an ongoing project and looks to overview design, details and behavior of the joints

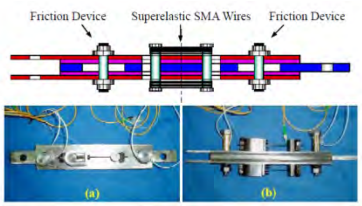
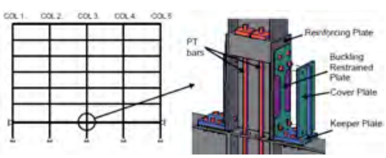
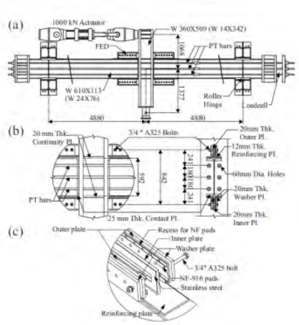
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
5.4 Christopoulos 02'	Component test on the energy-dissipating bars and large-scale exterior beam column joint test were conducted	Large-scale quasi-static cyclic loading test were performed on a strong table using an actuator	Energy-dissipating bars which are inserted into steel cylinders and welded to beam flanges	Yes	Yes, through high strength horizontal orientated PT	PTED provided good energy dissipation characteristics and was able to withstand large deformations without damage or residual drift
5.5 Pekcan 02'	1/3 scale model of a prototype end-sway frame was tested on a shake table	Subjected to five different ground motions with various peak ground accelerations, including the Kobe ground motion	Yielding fuse-bars with stable energy-dissipating mechanism	Yes	Yes, through elastomeric spring damper	Benefits included limited magnitude of support reaction transfer to the pier, reduced base shear response, shorter service time after major seismic events, and reduced axial force in the columns
5.6 Clifton 03'	4 large-scale experimental tests, two test on each of two specimens, were performed for each set up using a strong floor and actuator	Each joint was tested under two parts of loading, each of which having sets of 3 cycles reaching design capacities	FBJ energy dissipation provided through plate/beam element yielding and SHJ through sliding of the anchored cap plate	Yes	Yes, through joint resistance	The experimental results lead the author to believe the semi-rigid joints offer advantages of traditional rigid joints and could have potential use in the future

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.7 Dolce 04'		An existing R/C concrete building, was retrofitted with NiTi shape memory alloy (SMA) re-centering braces and transverse steel ties	R/C building structure designed for gravity loads only with no transverse frame	The existing building was divided into sections, retrofit bracing was provided, and experimental test were conducted	Assess the cyclic behavior of the retrofitted structure and compare with the existing structure's experimental performance
5.8 Carden 06'		I-girders with ductile end cross frames that use single angle X braces acting as structural fuses for straight two-girder bridges without skew	Steel girder bridges with ductile cross frames	Single angle component experiments were conducted and the performance of the system was tested through large-scale shake table test	Evaluate the performance of the X brace cross frame subjected to transverse earthquake excitation
5.9 Tremblay 08'		Self-centering energy dissipative (SCED) steel brace elements composed of friction energy dissipative mechanism and self-centering mechanism	System consist of steel bracing elements and pretensioned fiber tendons for steel frame buildings	Multi-story buildings are numerically analyzed using the SCED system and compared to conventional BRB systems	Compare performance of proposed system to conventional system analytically and lay out design considerations

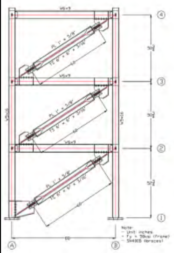
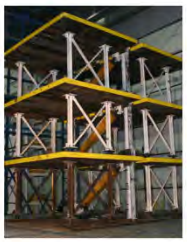
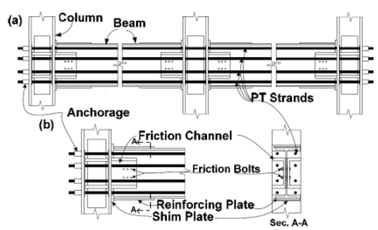
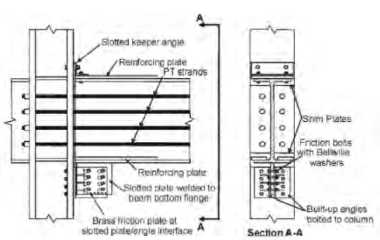
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
5.7 Dolce 04'	2-story existing R/C building was tested using a "reaction structure" with a hydraulic jack	Quasi-static cyclic tests and release test were performed on the bare frame and the retrofitted frame	Shape Memory Alloy braces with austenitic NiTi wires	Yes	Yes, through SMA braces	The braces provided strong re-centering capability, increased safety at Ultimate Limit State and displacement control at the Damage Limit State
5.8 Carden 06'	0.4 scaled single span model of a two girder bridge was tested on two reinforced elastomeric bearing using dynamic shake table experiments	Reversed static transverse loading was applied	Ductile X members showed enveloped hysteretic behavior providing the energy dissipation fuse	Yes	Yes, provided by top and bottom chord	The X brace frame showed capabilities of handling large drifts and the system demonstrated no apparent strength degradation, but has comparatively low post yield stiffness allowing energy dissipation
5.9 Tremblay 08'	2, 4, 8, 12, and 16-story buildings were modeled using a rigid diaphragm between braces and columns and two springs in series for the SCED brace	Models were excited with ground motion at 50, 10, and 2% of the50 year hazard level in Los Angeles	SCED member provides energy dissipation through steel friction connections	Yes	Yes, provided by PT strands	The analytical experiment showed SCED are a feasible alternative for BRB, as they reduce peak story drifts, eliminate residual deformations under low excitations, and offer better resistance against collapse

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.10 Zhu 08'	-	Self-centering friction damping brace (SFDB) consisting of friction energy-dissipating elements and self-centering superelastic elements	Frame uses shape memory alloys which provide centering capabilities and friction surfaces for energy dissipation	The proposed system is described and implemented for the displacement-based design process, and two design examples are presented	The paper intends to set up the design and analysis process for the SFDB system
5.11 Christopoulos 08'		System is based on continuing work of Tremblay et al. 2008 for Self-Centering Energy Dissipative (SCED) systems	Composed of traditional steel bracing elements, a dissipative mechanism, and a tensioning system which is used to pre-stress the device	The mechanisms of the SCED system are described and a series of component and system level experimental validations are analyzed	Evaluate system mechanisms on a component level and a preliminary system performance experimentally
5.12 Takamatsu 08'		A wedge device is proposed to minimize slip of an anchor-bolt-yield-type exposed column base and absorb energy	The wedge device is made up of a wedge, a counter-wedge and a spring, and can be implemented into differ proposed systems: non-slip type column-base, non-compression braces, and non-compression knee braces	The proposed wedge system was described, multiple experimental models were tested for each system and the results were compared	Evaluate the energy dissipation and restoring force characteristics of the different systems

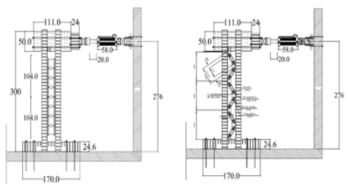
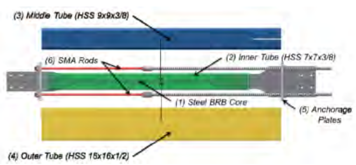
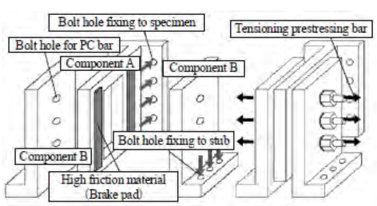
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
5.10 Zhu 08'	A 3 and 6-story model are designed as office buildings in downtown Los Angele	Three suites of earthquake ground motions were used in the nonlinear time-history analyses	Provided by friction slip details	Not specified	Yes, provided by SMAs	SFDB systems exhibit minimal residual drift and potential to be damage free after frequent and design basis earthquakes
5.11 Christopoulos 08'	Full scale testing of the system was performed on a strong floor with simple shear beam-to-column connection	A step-wise incremental quasi-static loading protocol and dynamic full scale test were performed	Slip critical bolted connections were used which included long slotted holes and faying surfaces for friction energy dissipation	Yes	Yes, through Aramid based tendon elements	A full scale validation of one possible embodiment of the system was analyzed and it was found to achieve stable and repeatable self-centering hysteretic response under cyclic loading protocols
5.12 Takamatsu 08'	Models were testing using a reaction beam, a reaction column, and a horizontal jack	Cyclic loading was simulated using the actuator	Energy dissipation is provided through column base gap opening and closing through the spring loaded wedge	Yes	Yes, restoring force provided by wedge and counter wedge interaction	It was found that non-slip-type column base and SC beam-to-column connections displayed predicted behavior and non-compression braces and non-compression knee-braces showed perfect elastic-plastic cyclic behavior without buckling or slipping

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.13 Qian 08'		Hybrid SMA friction devices (HSMAFD) consist of pre-tensioned superelastic shape memory alloy wires and friction devices	Proposed system is designed for steel frame buildings and is connected from bracing to floor beams	HSMAFD system was tested as a component and then implemented in a scaled structure and experimentally tested	Assess the performance of the energy dissipation devices in reducing dynamic response of structures under strong seismic excitation
5.14 Liu 08'		Post-tensioned column base connection with energy-dissipating plate connection	Column base connection for a seismic resistant PT steel frame is composed of PT high strength bars, buckling restrained steel plates, reinforcing plates, keeper plates and shim plates	The system design considerations are described and a FE analysis is performed	Propose performance-based design approach and evaluated the performance of the system through FE analysis
5.15 Kim 08'		Self-Centering Friction connection provide energy dissipation and restoring forces for column-to-beam connections	Steel MRF with SC horizontally PT elements and energy dissipating bolt-stressed friction devices	A new SCFR connection is described and examined experimentally through full-scale testing	Assess the performance of the SCFR connection under expected seismic loading for ductile behavior, energy dissipation, and residual story drifts

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
5.13 Qian 08'	¼ scale 3-story steel frame building was tested using a shake table	Three earthquakes on record were simulated for the time-history analysis	SMA damper used to dissipate energy through martensitic phase transformation in material	Yes	Yes, through SMA wires	The HSMAFD provided supplemental stiffness, reduced inter-story drifts and absolute displacements, and suppressed the dynamic response of the building
5.14 Liu 08'	A 2/3 scaled PT column base connection was modeled using a FE analysis	Loading sequence consisted of initial PT force, gravity load, bolt ED plates to column and grade beams, and apply cyclic lateral load	Energy dissipation was provided by buckling restrained steel plates	Yes	Yes, provided by post-tensioned high strength bars	Limit states for the connection were defined for the DBE and MCE and design equations provided an accurate prediction of connection moments, also the FM analysis was confirmed
5.15 Kim 08'	Full scale assembly testing was conducted for exterior and interior column-to-beam SCFR connections	The specimen was loaded under simulated incremental cyclic loading protocol	Bolt-stressed friction mechanism with a friction interface consisting of stainless steel and new non-asbestos organic break lining pads	Yes	Yes, through horizontal PT elements	The connection exhibited good energy dissipation without beam or column inelastic deformations and without residual story drift

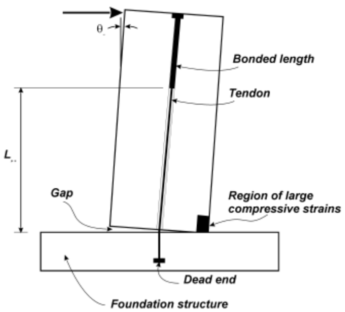
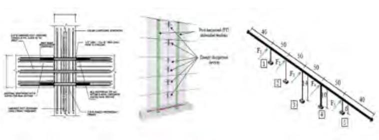
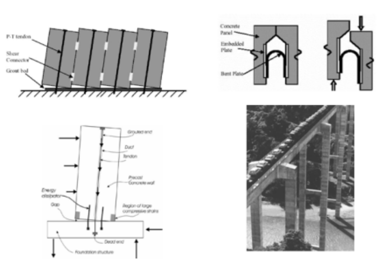
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.16 Bruneau 09'	 	Frame designed with BRBs working as metallic structural fuses while main structure remains elastic or with minor inelastic deformations	Steel frame with energy-dissipating braces	Frame and component configuration are described in detail and a scale model is tested	This paper aims to experimentally evaluate the performance of previous parametric analysis
5.17 Ricle 10'		A self-centering moment resisting frame (SC-MRF) is defined by a gap opening and closing at the beam-column interface with a restoring PT strand force	The beam-column connections for steel frame buildings consist of PT strands and energy-dissipating web friction devices (WFD)	A prototype building is analyzed using a performance-based design procedure and a scaled model is developed and tested	Evaluate the proposed connection for a MRF analytically and experimentally
5.18 Wolski 09'		SC-MRF with a Bottom Flange Friction Device providing energy dissipation	Steel self-centering moment resistant frame with horizontal PT strands and BFFD	The BFFD design and detail is examined and large-scale testing is conducted	Investigate the effect of the BFFD friction force, connection details, and assess performance under cyclic loading

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
5.16 Bruneau 09'	1/3 scale model of a 3-story frame was tested on a shake table	BRB were axially tested and the system was tested under standard loading protocol and low-cycle fatigue test	BRBs fuse elements consisted of passive energy dissipation metallic dampers	Yes	Yes, through BRB energy dissipation and connections	Analytical models generally represented the fuse behavior and the BRB connections provided a fuse element with replacement capabilities
5.17 Ricle 10'	0.4 scale 4-story 2-bay SC-MRF frame was tested using hydraulic actuators	A lateral force was applied at each level using a hybrid simulation method and four DBE motions	WFD connection with friction channels welded to the column flange and brass cartridge plates sandwiched between the webs of the channels and beams	No	Yes, provided by horizontal PT strands	SC-MRF performed well under DBE level ground motions, and the connections provided reasonable levels of energy dissipation while exhibiting self-centering capabilities and little damage
5.18 Wolski 09'	Seven 0.6-scale test specimens were experimentally examined for behavior under seismic simulated load	Symmetric lateral displacement cyclic cycles were applied through an actuator	BFFD provide energy dissipation through a friction sliding surface between a brass plate and slotted bolted plates	If designed in accordance to recommendations, would not be necessary to replace	Yes, through horizontal PT high-strength steel strands	If designed as suggested the BFFD provided significant energy dissipation and the connection remained damage free through the loading

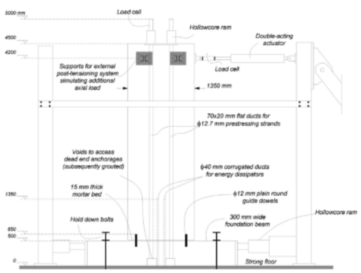
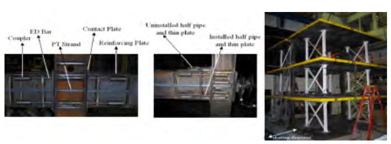
Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
5.19 El-Bahey 10'		Proposed twin column bridge pier bent concept with a series of structural fuses	Twin pier bents with connecting structural fuses for energy dissipation	Experimental tests were conducted for the system with two different structural fuses and then for the bare frame	Apply innovative multi-column accelerated bridge construction pier concept and evaluate seismic performance for different fuse configurations
5.20 Miller 11'		Self-centering BRB supplemented with pre-tensioned superelastic NiTi SMA	Replacement for conventional BRB in steel frames	A numerical model is created and material property testing in conducted	Validate numerical model and close examine material properties for SC-BRB units
5.21 Sanada 11'		Two component bolted assemblage with a damping high friction material (brake pad) and tensioned prestressing bars	Damper is applied to upper and lower surfaces of beam members for prestressed concrete buildings	Component test are conducted and an experimental test is performed for the damping system installed on a PC beam specimen	Study the behavior of the proposed damping design for potential applications

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
5.19 El-Bahey 10'	Two 2/3 scale models were developed and tested using an actuator and strong wall	Three quasi-static tests were performed up to a drift corresponding to the onset of column yielding and then continued till failure	Steel plate shear links and buckling restrained braces in series	Yes	Yes, provided by self-weight	The fuse concept demonstrated increased strength and stiffness while the bridge pier remained elastic and energy was dissipated
5.20 Miller 11'	Four sample specimens were heat treated and tested	Series of quasi-static cyclic tensile test were performed	Energy is dissipated through NiTi SMA	Yes	Yes, provided by SMA wires	Least amount of residual elongation occurred after heat treating the bars for 60 minutes after machining them and final brace design was chose to limit overall strain in the SMA to less than 5%
5.21 Sanada 11'	A compression test was carried out for the damper and a full scale test using a horizontal jack was conducted on a PC beam specimen with the damping system	Reverse cyclic loads were applied and the tension force was varied during the test	Energy dissipation is provided by friction pad	Yes	Yes, through prestressed concrete	It was found that the damper increased overall strength and energy, but asymmetric contributions observed and believed to be caused by different axes of rotation in both the loading directions

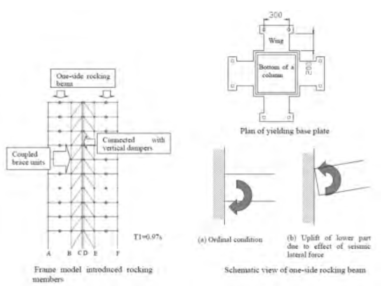
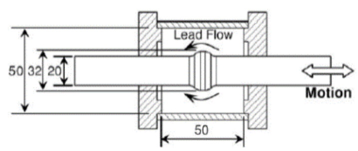
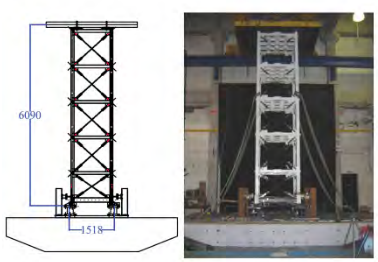
7.5. Table 5 Structures with Rocking, Self-Centering and Energy-Dissipating Fuses

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
6.1 Restrepo 01'		A precast concrete wall with unbonded self-centering prestressed tendons, rocking capabilities and energy-dissipating mild steel yield bars	Precast concrete wall jointed at the base with prestressed partially unbonded tendons	An analytical model of a 12-story cantilever wall building is tested and results are discussed, followed by the experimental testing of 5 wall specimens	Provide design aspects for a structural system which looks to minimize damage and validate design experimentally
6.2 Palermo 04'		Hybrid controlled rocking concept with energy-dissipating sacrificial devices for bridge systems	Pier and foundation and/or pier and deck section interfaces	An analytical analysis of single and multi-degree of freedom bridge controlled rocking systems is outlined	Integrate advancements in seismic performance of precast concrete buildings into bridge systems
6.3 Restrepo 04'		Optimal Earthquake-resistant system: (i) Limit induced seismic forces through nonlinear characteristics of yielding, (ii) Encompass self-centering properties, (iii) Reduce cumulative damage to structural elements	Several reinforced concrete and steel configurations are examined	Examine the background of self-centering systems and describe research regarding self-centering reinforced concrete walls, confined masonry walls, steel structures and bridge structures	Briefly describe some of the latest self-centering structural systems

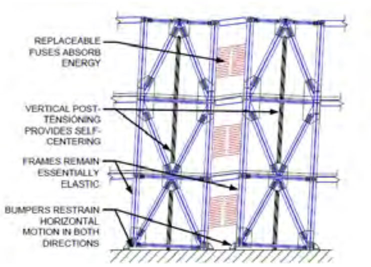
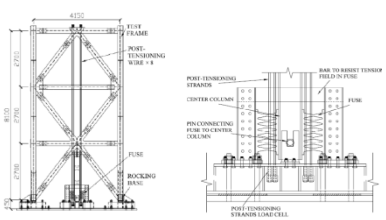
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
6.1 Restrepo 01'	Five ½ scale wall specimens, representing the walls of a prototype 4-story building, were tested using a double acting hydraulic actuator	Quasi-static reverse cyclic loading to increasing drift levels was applied	Mild steel bars with a milled segment in the form of a "dog-bone"	Yes	Yes, through prestressed partially unbonded tendons	The jointed walls allowed gap opening and closing with 2.5% drift and only cosmetic damage and cycles to 4% drift with no strength degradation
6.2 Palermo 04'	Analytical model of three bridge systems with different mechanical properties was created	Seismic response examined through push-pull cyclic and non-linear time-history analyses	Modeled for yielding mild steel bars	Yes	Yes, through PT cables	Integrating a rocking section interface can lead to significant damage reduction in the pier element and could limit repair cost to the replacement of the fuse system
6.3 Restrepo 04'	-	-	-	-	-	Economical earthquake-resistant structural systems with large lateral displacement capacity, minimized structural damage after displacements and self-centering capabilities were reviewed

Author	**Representative Figure**	**Description of System**	**Frame Configuration**	**Experiment Synopsis**	**Purpose of Research**
6.4 Bruneau 07’		Author describes the research regarding structural fuse concept in BRB frames, rocking truss piers and steel plate shear walls	Steel MRF, steel truss piers and shear walls are examined	Review developments in recent hysteretic-based systems and compare with conventional structural configurations	Provide a competitive and effective structural configuration for a seismic resistant system
6.5 Restrepo 07’		Self-centering structural wall allowed to rock about foundation with PT vertical strands and longitudinal energy dissipating devices	Jointed precast cantilever wall	Half scale tests were performed on a rocking wall and a hybrid rocking wall with energy dissipators to validate prediction models and study behavior	Assessed for life safety performance objectives: prevent base sliding shear, preclude yielding of the tendons, avoid fracture of energy dissipator, prevent loss of integrity, and minimize loss of stiffness
6.6 Wang 08’		Steel plane frame with self-centering and post-tensioned strands along with fuse elements	Steel plane frame with yielding elements in each beam-to-column connection	Experimental testing of a fully-welded steel MRF and a SCPT frame was performed and compared	Evaluate the performance of the proposed seismic resistant system

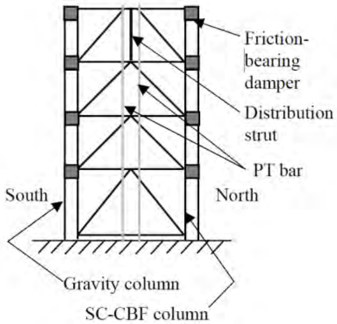
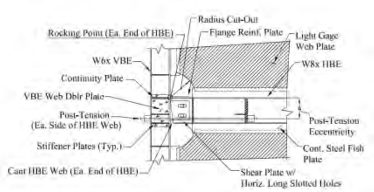
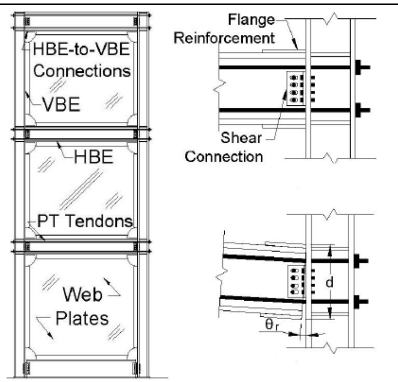
Article	**Test/Analytical Setup**	**Test Load Conditions**	**Description of Fuse(s)**	**Replaceable**	**Self-Centering System**	**Conclusions**
6.4 Bruneau 07'	-	-	-	-	-	The paper provides an overview of developments in seismic design that incorporate rocking and energy-dissipating structural elements
6.5 Restrepo 07'	Three half scale test specimens were tested; two with energy dissipating "dog-bones" and one without	Specimens were subjected to quasi-static reverse cyclic loading through a double-acting actuator	"Dog-bones" are machined mild steel reinforcing bars with a section of smaller diameter over a specified length; they were cast into the foundation and grouted into the wall	No	Yes, through gravity load and vertical prestressed unbonded tendons	Hybrid rocking system provided good energy dissipation, had minimal structural damage, no residual drifts, and met all of the safety performance objectives
6.6 Wang 08'	Two 1/3 scale 3-story 2-bay frames were tested using a shake table	A ensemble of 25 synthetic MCEER simulated earthquake records were used for the ground motion that was run in two series (forward and reverse)	Energy-dissipating yield bars	Yes	Yes, through PT strands	The SCPT model provided a reduction in acceleration response, ED performed accordingly minimizing damage to the beams, and overall good seismic performance was observed

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
6.7 Azuhata 08'		Self-centering system with rocking structural members and yielding base plates	Analytical model of a steel MRF was created	Analytical seismic response analyses are performed on a full scale steel frame model using an artificial ground motion	Examine the behavior and response of the proposed system
6.8 Rodgers 08'		A 10-story prototype building was examined in 3 locations for energy dissipation performance and a damping device is introduced as a fuse element	RC prototype building with energy-dissipating zones located at exterior PT RC connection, corner exterior PT RC connection and a steel connection	Experimental testing of the proposed system was conducted for the connection details and results were discussed	Validate performance of high force to volume damper in structural connections and energy dissipation
6.9 Polinoo 10'		Controlled rocking steel truss with passive energy dissipative devices	Bridge steel truss pier with dampers located at the base	Scaled experimental shake table testing based on previous analytical modeling and research	Measure experimental quantities including displacement, strains, and member forces and compare to analytical predictions for seismic behavior

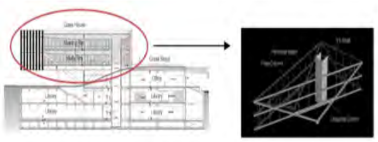
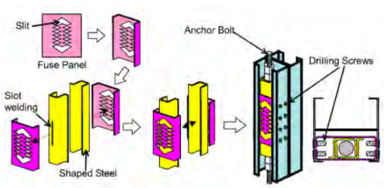
Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
6.7 Azuhata 08'	10-story model of a conventional brace frame and the proposed self-centering model with rocking structural members were created	An artificial ground motion and the 1995 JMA Kobe NS were inputted	Yielding base plates	Yes	Yes through rocking, yielding members and self-weight	It was found the vertical connection dampers arrangement plays a significant role in the seismic response and further evaluation is needed
6.8 Rodgers 08'	A 3D RC beam-column exterior joint sub assemblage and a beam-to-column steel connection were tested using an actuator set up	Quasi-static loading consisting of fully-reversed sinusoidal displacement cycles were applied	High force to volume damping device (HF2V) composed of a bulged central shaft which induces a plastic flow of lead during shaft motion to provide a resistive force	Yes	Yes, provided by resilience of HF2V system	The HF2V system provided adequate level of energy dissipation, offered high force and did not suffer from low-cycle fatigue allowing self-centering capabilities
6.8 Polinoo 10'	1:5 Scaled bridge steel truss pier or a typical 2 lane highway bridge, tested using a shaking table	Excitations from record of the 94' Northridge EQ and a synthetically generate record were implemented	Three sets of steel yielding devices and a set of fluid viscous dampers	Yes, and retrofitting possibilities	Yes, provided by selected damping system	Experimental results showed a maximum relative pier displacement of 3.9% drift and 82 mm of uplift, but none of the structural members were damaged; also, the observed values of displacement and force were found to vary at time from the predicted results

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
6.10 Hamid 09'		Six prestressed concrete hollow core units; two load-bearing units bound to foundation through unbonded vertical tendons and four units acting as nonstructural cladding	Super-assemblage of precast hollow core for lateral seismic performance	Previous research was examined and a model of the proposed system was experimentally tested	Investigate relative contributions of strength and equivalent viscous damping of the components of the multi-panel wall system
6.11 Eatherton 10'		Controlled rocking frame with self-centering PT strands and energy-dissipating fuses	Dual frame configuration with a center vertical spine of fuses	The paper summarizes hybrid simulation testing and previous work including test on fuse topologies, FEM modeling of the fuses, a parameter study, and large-scale cyclic testing	Validate the performance of the system from experimental testing and predict behavior through analytical modeling
6.12 Ma 10'		Controlled rocking frame with self-centering PT strands and energy-dissipating fuses	Single rocking frame configuration with PT strands and fuses located along the centerline of frame	Large-scale testing was performed to further work by Eatherton et al. 2010 and a numerical analysis was conducted	Provide an analytical model and validate behavior predictions through experimental testing of a controlled rocking seismic energy-dissipating system

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
6.10 Hamid 09'	Full-scale testing took place on a strong floor with a reaction frame and actuator	Tested under in plane quasi-static reverse cyclic loading	Longitudinal unbonded prestressed tendons with a reduced diameter section	Yes	Yes, by elastically elongating tendons	Experimental results show the assemblage can be used in design of single story warehouses and it was recommended that each seismic wall panel be located at the center of a single precast foundation beam unit
6.11 Eatherton 10'	A ½ scale specimen was tested under two dimensional loading using a Loading and Boundary Condition Box	Quasi-static cyclic loading was applied to five dual frame configurations and two single frame configuration and quasi-static hybrid simulation loading was applied to two dual frames	Yielding steel plates with diamond shaped cut-outs	Yes	Yes, provided by vertical PT strands	Large-scale testing provided validation of the performance of the system; residual drift was minimized and the frames remained elastic while the damage was concentrated at the fuses
6.12 Ma 10'	A 2/3 scale 3-story specimen was tested using a shake table	Four test were conducted using simulated ground motions JMA Kobe NS and Northbridge Canoga	Three fuse types were investigated: non-degrading butterfly fuse, degrading butterfly fuse, and buckling restrained brace	Yes	Yes, provided by vertical PT strands	An FEM model was developed and proved accurate for predicting behavior of the system, the design criteria and constructability was exhibited, and key parameters including SC, rocking column bases and damage control were validated through experimental testing

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
6.13 Sause 10'		Self-centering CBF with rigid-body rotation of the frame and uplift resistance provided by vertically-aligned PT steel	CBF with fixed gravity columns and SC-CBF columns which are separated by friction-bearing dampers	The proposed system was modeled using OpenSees and experimentally tested, then compared to a limit state and performance-based seismic design procedure	Evaluate seismic performance of SC-CBF and provide a performance-based seismic design procedure
6.14 Downden 11'		Post-tensioned rocking moment connection (PT-RMC) which eliminates beam growth by maintaining constant contact of the beam top flange and the column during lateral drift	Steel connection which allows gap opening with independently anchor PT chords providing the restoring force	The NZ-BREAKSS connection is described in detail and an analytical model is created to examine the behavior	Compare the proposed design to other PT-RMC connection designs
6.15 Clayton 11'		Self-centering steel plate shear walls (SC-SPSW) with post-tensioned rocking beam connection	PT rocking moment connections allow joint gap opening between VBE and BHE interface while PT elongation provided SC mechanism	The system behavior is examined through free body force diagrams, design consideration for the connection are detailed and an analytical model is created and tested	Provide an overview and performance evaluation of SC-SPSW and system fundamental behavior through analytical analyses, and provide a performance-based design for the system

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
6.13 Sause 10'	0.4 scale 4-story 2-bay SC-MRF frame was tested using hydraulic actuators	Numerous simulated earthquakes using the hybrid simulation method was applied	Friction-bearing dampers located so that slip can occur due to the relative vertical displacement between the SC-CBF columns and gravity columns	Yes	Yes, provided by vertical PT strands	The described performance objectives were met and related analytical predictions matched experimental results generally, also under the DBE-level ground motions no significant structural damage occurred and in all cases the structure re-centered
6.14 Downden 11'	An analytical model was created using SAP2000	Cyclic nonlinear static pushover analysis was conducted and a time-history analysis was performed to verify self-centering performance	Energy dissipated through rocking and PT chords	Yes	Yes	Damage to the floor diaphragm is mitigated through rocking connection with essentially no beam growth and the system provided self-centering capabilities
6.15 Clayton 11'	A numerical model was developed in OpenSees	Model was subjected to suite of ground motions based on the SAC project for the Los Angeles site and a series of nonlinear response history analyses were conducted	Unstiffened ductile web plates	Yes	Yes, provided by PT rocking beam connections	The preliminary results exhibit that the SC-SPSW system could be an alternative to the traditional lateral force resisting system, but more validation is needed including experimental work

Author	Representative Figure	Description of System	Frame Configuration	Experiment Synopsis	Purpose of Research
6.16 Takeuchi 11'		Recent seismic design concepts project on the Tokyo Tech O-okayama campus are described including the performance of the superstructure of the library and energy-dissipating louver retrofit design for the Secretariat Building	The Secretariat building is retrofitted with energy-dissipating horizontal and diagonal louvers acting as BRBs	A mock-up test of the louvers was performed and the system has been implemented on the structure	The paper outlines applications of ongoing research on the Tokyo Tech O-okayama campus
6.17 Ozaki 13'		Small-sized hold-downs with a built-in fuse function for energy dissipation and controlled rocking	Multistory Steel sheet shear walls with HDFs implemented at column base and foundation connections	The fundamental behavior of the HDFs is examined through full scale shake table testing	Experimentally investigate and compare the HDF system to identical systems without the fuse device
-	-	-	-	-	-

Article	Test/Analytical Setup	Test Load Conditions	Description of Fuse(s)	Replaceable	Self-Centering System	Conclusions
6.16 Takeuchi 11'	A full scale test of the louver was conducted	Cyclic testing was performed	Louver BRBs provide energy dissipation through hysteretic damping	Yes	Yes, through hysteretic behavior of the louvers	The structures are now designed and retrofitted to withstand level-2 earthquake and are expected to be usable after such a seismic event
6.17 Ozaki 13'	Full-scale shake table test were performed on four 1-story single span steel sheet shear wall specimens with varying connection types	Cyclic loading was conducted using the El Centro EQ and Kobe EQ records	The HDF consist consists of a pair of fuse steel plates slot-welded to a U-shaped steel channel which is placed between the rocking frame and the foundation	Yes	Yes, through vertical gravity loads	The HDFs exhibited good energy dissipation capacity and reduced base-shear and uplift deformations, but it was noted a residual displacement of 0.5 mm was found and further investigation is needed
-	-	-	-	-	-	-

8. List of Abbreviations and Symbols

A: Frame Width

BDSP: Braced Ductile Shear Panel

BF: Bare Frame

BFFD: Bottom Flange Friction Device

BNC: Bone in Cone

BRB: Buckling Restraint Braces

BPY: Base Plate Yielding

CBF: Conventional Concentrically Braced Frame

CC: Conventional Construction

Cf: Compression Acting Brace

CQC: Complete Quadratic Combination

CRBF: Controlled Rocking Braced Frame

CRS: Controlled Rocking System

CSI: Core Suspended Isolation System

CSF: Cast Steel Yielding Fuse

DAD: Damage Avoidance Design

DBE: Design Bases Earthquake

DLE: Design Level Earthquake

DSFD: Double Surface Friction Dissipaters

EBF: Eccentrically Braced Frame

ED: Energy Dissipation

EDD: Energy-dissipating Device

ESQ: Elastomeric Spring Dampers

EQ: Earthquake

FBJ: Flange Bolted Joint

FCB: Fuse Coupling Beam

FIX: Fixed-Base

Fpti: Initial Post Tensioning Force

FRD: Foundation Rocking-Dominated

h: Height

HBE: Horizontal Boundary Element

HF2V: High Force to Volume

HPFRC: High Performance Fiber Reinforced Concrete

HSMAFD: Hybrid Shape Memory Alloy Friction Device

HSS: Hollow Structural Sections

INSTED: Innovative Stiffness and Energy Dissipation System

LCC: Life Cycle Cost

LD: Limited Ductility

LF: Lateral Force

MCE: Maximum Considered Earthquake

MD: Moderately Ductile

MR: Moment Resisting

MRSF: Moment Resisting Steel Frame

NewZ-BREAKSS: New Zealand-inspired-Buffalo Resilient Earthquake resistant Auto-centering while Keeping Slab Sound

NIP: Nonlinear Impulse Procedure

NiTi: Nickel-Titanium

OM: Overturning Moment

(OM)d: Design Overturning Moment

OMRF: Ordinary Moment Resisting Frame

OT: Overturning Ratio

PBEE: Performance Based Earthquake Engineering

PC: Pre-stressed Concrete

PED: Passive Energy Dissipation

PT: Post Tensioning

PTED: Post-tensioned Energy-dissipating

PT-RMC: Post Tensioned Rocking Moment Connection

PT-SCED: Pre-Tensioned Self-Centering Energy Dissipative

RC: Reinforced Concrete

RCFB: Retrofitted Chevron-Braced Frame

RD: Roof Drift

RDis: Roof Displacement

RH: Roof Height

RHA: Response History Analysis

SC: Self-Centering Ratio

SCB: Steel Coupling Beam

SCED: Self-Centering Energy Dissipative

SCFR: Self-Centering Friction

SCPT: Self-Centering Post Tensioned

SCR: Self-Centering Model with Rocking Structural Members

SC-SPSW: Self-Centering Steel Plate Shear Wall

SFDB: Self-Centering Friction Damping Brace

SFRS: Seismic force Resisting Systems

SHD: Structural Hinging-Dominated

SHJ: Sliding Hinge Joint

SIWIS: Seismic Infill Wall Isolator Subframe

SMA: Shape Memory Alloy

SMRF: Special Moment Resisting Frame

SPSW: Steel Plate Shear Wall

SC-CBF: Self-Centering Conventional Concentrically Braced Frame

SC-MRF: Self-Centering Moment Resisting Frame

TBD: Toggle-Braced Damper

T/C: Tension Compression

Tf: Tension Acting Brace

TFD: Tendon Fuse + Damper

T/O: Tension Only

UPT: Unbounded Post Tensioning

VDCSR: Viscously Damped Controlled Seismic Rocking

VBE: Vertical Boundary Element

Vp: Plastic Fuse Capacity

WFD: Web Friction Device

- : Not available

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REPORT NO.	AUTHORS	TITLE	DATE
NEU-CEE-2013-01	Hajjar, J. F.; Sesen, A. H.; Jampole, E.; Wetherbee, A.	A Synopsis of Sustainable Structural Systems with Rocking, Self-Centering, and Articulated Energy-Dissipating Fuses	June 2013
NEU-CEE-2011-01	Hajjar, J. F.; Guldur, B.; and Sesen, A. H.	Laboratory for Structural Testing of Resilient and Sustainable Systems (STReSS Laboratory)	September 2011