Toward a Performance-Based Design Framework For Self-Centering Rocking Braced-Frame Spine Systems

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SUMMARY
Recent studies by the authors and others have demonstrated the viability of seismic resisting systems that employ controlled rocking to provide self-centering action and can resist large earthquake ground motions with minimal structural damage or residual drifts. Proposed structural systems include rocking steel braced frames and concrete walls, both of which often employ post-tensioning to enhance the natural self-centering action of gravity loads. The design issues and criteria for controlled rocking systems are examined, with particular emphasis on a steel braced-frame system that has been studied through an extensive series of tests on three-story rocking frame prototypes, including half-scale quasi-static tests, and two-thirds scale three-story shake table tests. These tests, combined with supporting analyses, demonstrate that the proposed systems can sustain extreme ground motions (return periods on the order of 1,000 to 2,500 years) with drifts up to 3% without any permanent deformations or damage to the structural system.

Keywords: Self-Centering, Structural Fuses, Large-Scale Experimentation, Controlled Rocking, Spine Systems

1. INTRODUCTION

In spite of the much advancement to improve the seismic safety of building systems, modern building systems are prone to significant structural damage from large earthquakes, including the potential for large residual drifts that can lead to building closure and demolition. Recently, practicing engineers and researchers have explored the use of seismic resisting systems that employ elastic spines with controlled rocking and self-centering action to minimize and potentially eliminate structural damage and residual drifts due to earthquakes. Proposed structural systems include rocking steel braced frames and concrete walls, both of which often employ post-tensioning to enhance the natural self-centering action of gravity loads. This paper will examine design issues and criteria for controlled rocking systems, with particular emphasis on a steel braced-frame system that has been studied through computational simulations, large-scale tests and archetype design applications.

2. OVERVIEW OF SELF-CENTERING STEEL BRACED ROCKING FRAME

One implementation of the self-centering rocking spine system is shown in Figure 2.1, where the rocking spine consists of a steel braced frame that is designed to remain essentially elastic by rocking off its foundation during large earthquakes. Overturning is resisted by a combination of gravity loads on the frame, post-tensioning tendons, and shear fuses. Capacity design principles are employed to ensure that the braced frame can sustain the forces induced during rocking, and that the braced frame and surrounding gravity framing system can sustain the rocking deformations without significant damage. The rocking frame base would typically consist of a steel armored trough (in a concrete footing) with a depth that exceeds the maximum expected uplift, and where base shear forces are resisted through bearing between the seated column and the edge of the trough. As illustrated in Figure 2.2, there are many other possible configurations of the rocking frame, including a dual frame configuration (Figure 2.2b) where fuses are located between two adjacent frames, configurations with alternate fuse types (Figure 2.2c), or alternative locations of the fuses and/or post-tensioning (Figures 2.2d to 2.2f).

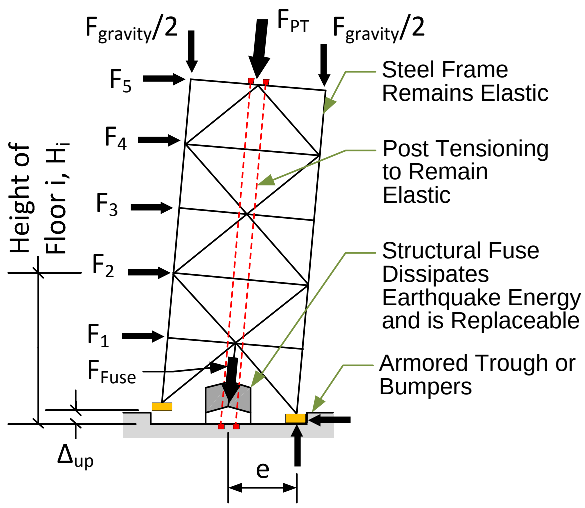


Figure 2.1. Rocking Steel Braced Frame Spine System

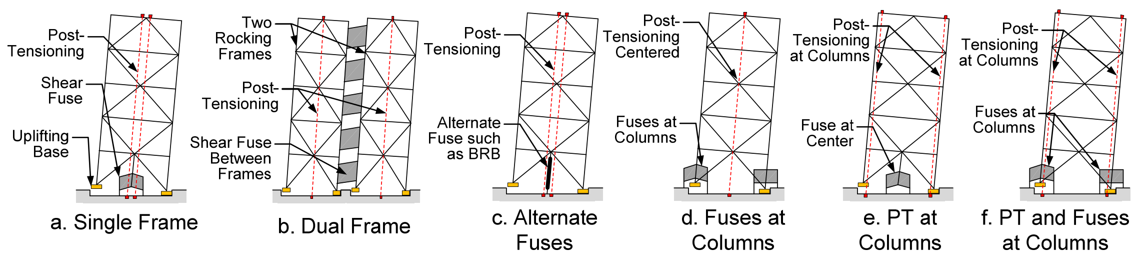


Figure 2.2. Alternative Configurations of the Rocking Steel Frame System

The overall response of the self-centering rocking frame is described by the idealized flag-shaped hysteretic response in Figure 2.3a, which results from the combined nonlinear elastic response of the rocking post-tensioned frame (Figure 2.3b) combined with the inelastic hysteretic response of the shear fuses (Figure 2.3c). The nominal overturning moment resistance for the single-frame configuration is given by the following equation, which is a simple summation of the resistance provided by gravity loads, post-tensioning (PT), and the structural fuse:

$$M_{resist} = \sum F_{gravity} e_{gravity} + F_{PT} e_{PT} + F_{fuse}\, e_{fuse} \tag{1}$$

where F and e are the forces and rocking eccentricity of each mechanism that provides overturning resistance. Provided that the post-tensioned rocking resistance (M_{up}) is larger than the elastic-plastic fuse strength (M_{fsy}), then the frame can statically self-center, as shown in Figure 3a. As described later, the ratio between these two components is a key design consideration to balance the amounts of self-centering tendency to energy dissipation.

Referring to Figure 2.3, for design purposes, the nominal yield strength, M_y, is equal to the sum of overturning resistances, M_{up} and M_{fsy}, associated with the gravity dead loads, the initial PT force and the yield strength of the fuse. The resulting yield moment is given by the following:

$$M_y = \sum F_{DL}\, e_{DL} + f_{PT,o}\, A_{PT}\, e_{PT} + F_{fs,y}\, e_{fuse} \tag{2}$$

where F_{DL} is the tributary dead load on the frame, $f_{PT,o}$ is the initial stress in the post-tensioning, A_{PT} is the area of PT, and $F_{fs,y}$ is the yield strength of the fuse. Beyond uplift, the overturning resistance increases with increasing drift ratio due to elastic straining of the PT and strain hardening of the fuse. Assuming that the drift ratio is equal to the uplift angle, the overturning resistance, M_c, at a given drift ratio, δ_c/h, is equal to the following:

$$M_c = M_y + \left(K_{PT} + K_{fs}\right)\left[\left(\delta_c / h\right) - \left(\delta_y / h\right)\right] \tag{3}$$

where h is the frame height, δ_y is the story drift at yield, the hardening stiffness's are given by the following:

$$K_{PT} = {E_{PT} A_{PT} e_{PT}^2} \big/ {L_{PT}^2} \tag{4}$$

$$K_{fs} = k_{fs,sh} e_{fs}^2 \tag{5}$$

and where, E_{pt} is the effective modulus of elasticity of the PT, L_{pt} is the length of the PT, $k_{fs,sh}$ is the strain hardening stiffness of the fuse, and the other terms are as defined previously.

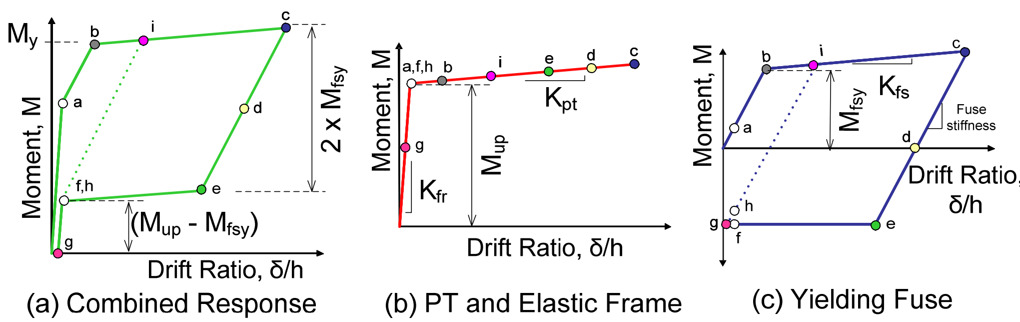


Figure 2.3. Behavior of Self-Centering Rocking Systems

3. OTHER ELASTIC SPINE SYSTEMS

The steel rocking frame illustrated in Figures 2.1 and 2.2 is one example of elastic spine systems that employ controlled rocking and self-centering action to improve seismic performance. The concept of the elastic spine can refer to lateral resisting systems of any materials that have a stiff elastic element spanning multiple floors, which enforces the story drifts to follow a relatively linear pattern across floors. This effect has been referred to as mode-shaping (Mar 2010), since the elastic spine controls the deformation pattern in the building and prevents the formation of localized story mechanisms. Conventional concrete shear walls designed to develop a ductile flexural hinge at the base act as elastic spines, though conventional walls will typically not have enough gravity loads to self-center.

In the past two decades there have been several new applications of spine systems using precast concrete shear walls and steel braced frames. The precast PT concrete shear walls in **Figure** a are quite similar to the controlled rocking steel braced frame discussed in the previous section with the main difference being that the energy dissipation is realized through yielding of mild steel reinforcing bars. This system was developed as part of the Precast Seismic Structural Systems (PRESSS) research program (e.g. Priestley et al. 1999, Kurama et al. 1999) and specimens similar to those shown in

Figure 3.1a were tested by Holden et al. (2003) and others. Recently, Panian et al. (2007) have employed similar concepts to apply PT to cast-in-place concrete walls to provide self-centering response while also easing congestion by replacing a portion of the mild steel reinforcement with PT steel. The PRESSS program also developed the jointed precast concrete wall system (Nakaki et al. 1999, Sritharan 2009), shown in Figure 3.1b, which is similar to the dual-configuration rocking frame (Figure 2b) and uses special shear yielding connectors between the rocking precast walls to dissipate seismic energy. Luth et al (2008) describe a similar application of shear yielding connectors to dissipate energy in cast-in-place rocking walls. Design guidelines and criteria for the precast PT walls are available in ACI ITG (2007, 2009).

Several variations on the steel rocking frame concept are shown in Figures 3.1c through 3.1e. The rocking frame with friction dampers (Figure 3.1c) was developed and tested by Sause et al. 2010. This system is unique in the way the lateral load is transferred to the rocking frame through a bearing joint between the rocking frame column and an adjacent column. The bearing connection also dissipates energy in an amount proportional to the magnitude of the bearing force. Mar (2010) designed a trussed mast frame, shown in Figure 3.1d, for the Gar Building in Berkeley, California. The mast system was shown to not only prevent undesirable single story mechanisms, but also engage all buckling restrained braces during inelastic lateral motion. This configuration allowed the use of fewer buckling restrained braces and thus cost savings as compared to a more standard chevron configuration of buckling restrained braces. Finally, Weibe and Christopoulos (2009) have tested PT braced frames with multiple rocking sections for braced steel frames as shown in Figure 3.1e. The additional rocking locations are envisioned as an effective way to control seismic force demands in tall frames where higher mode effects are significant.

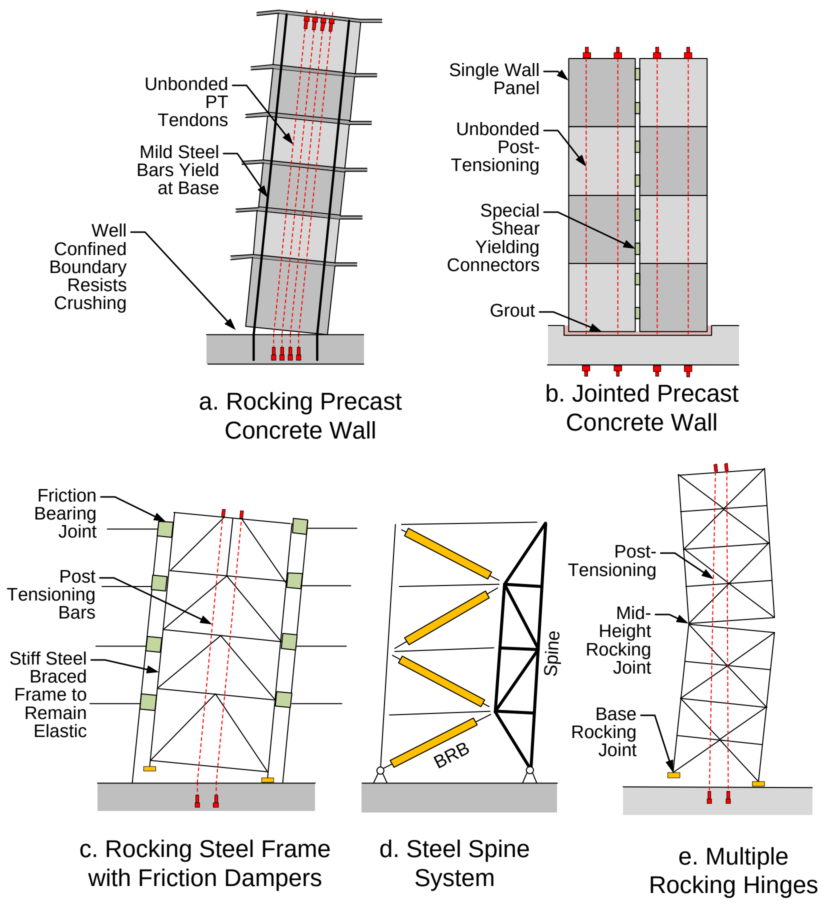


Figure 3.1. Other Spine Systems Used in Research and Practice

The wide variety of systems illustrated in Figures 2.2 and 3.1 demonstrate the versatility of framing concepts that employ common features of elastic spine systems with articulate hinge regions, combined with inelastic energy dissipation devices to dampen response and post-tensioning to enhance self-centering action. Common to all of these systems is the establishment of a minimum required overturning resistance, which is provided through a combination of self-centering rocking action (Figure 2.3b) and inelastic yielding (Figure 2.3c). An additional important consideration for elastic spine systems is determination of the induced shear forces for capacity design of the concrete wall or steel bracing system. It has been shown in several studies that although the story shear forces associated with first mode behavior are limited by the inelastic rocking mechanism, that the forces associated with higher modes (being resisted elastically) can be significantly larger than the design forces for conventional braced frames (e.g. Roke et al. 2008). Design procedures accounting for this effect have been proposed for conventional concrete shear walls (Mesa and Priestley 2002) as well as rocking steel braced frames (Roke et al. 2008, Pollino and Bruneau 2004, Eatherton and Hajjar 2010, and Ma et al., 2011a). The design methodologies involve combining reduced elastic forces associated with first mode deformations with unreduced elastic forces associated with higher mode deformations, amplifying higher mode forces, or amplifying story shears calculated using a capacity design method.

4. ENERGY DISSIPATING FUSES

One of the innovations in the rocking frame research was the development of ductile energy dissipating fuses, which are designed with well-controlled yield strength and to sustain large inelastic deformations. As shown in Figures 4.1 and 4.2, the fuses consist of mild steel plates which are fabricated using water-jet cutting into butterfly shaped links to distribute inelastic strains and, thereby, sustain large deformations prior to fracture. The fuses were originally developed for the dual frame configuration (Figures 2.2b and 4.1b), where the fuses are positioned between the frames and subjected to shear deformations. Later, the same design was reconfigured to work in opposing pairs of links (Figures 2.1 and 4.1a) to provide a tension/compression fuse in the single rocking frame.

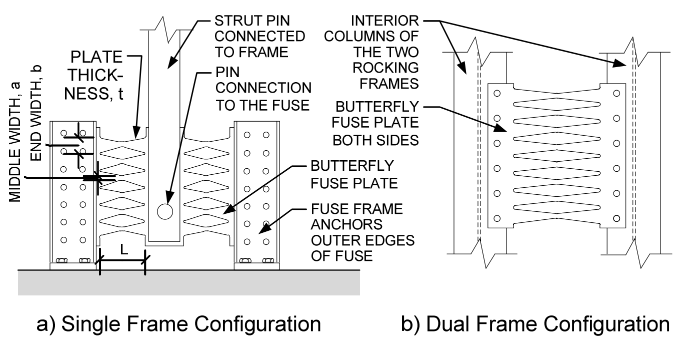


Figure 4.1 Butterfly Fuse Plates

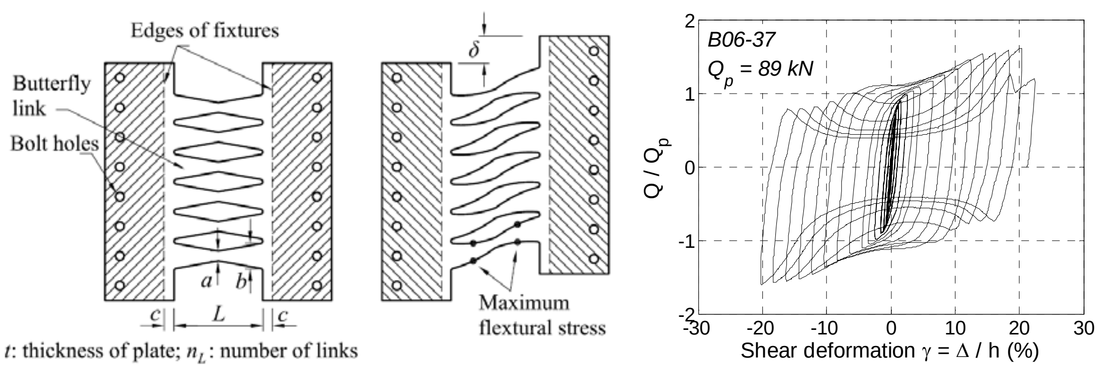


Figure 4.2 Behavior of Butterfly Fuse Plates

As shown in Figure 4.2, the shear fuses are able to sustain shear deformations of at least 20% (measured over the butterfly link lengths) prior to fracture. The links initially respond in flexure with fat hysteresis loops, and then, depending on the slenderness of the links (mainly the link width to thickness ratio, b/t) the links undergo torsional-flexural buckling, causing the hysteretic response to become pinched. While the pinching reduced the amount of energy dissipation, the pinching at large deformations is desirable to enhance self-centering of the frame. Details of the fuse testing and design method are summarized by Ma et al. (2011b)

5. LARGE-SCALE EXPERIMENTAL VALIDATION

The rocking frame concepts were validated through large-scale testing, conducted at the University of Illinois NEES lab and the E-Defense shaking table in Miki, Japan. Half-scale quasi-static tests of the dual and single frame configuration were conducted at the NEES lab, and two-thirds scale shaking table tests of the single frame configuration were conducted at E-Defense. The frames were designed based on a three-story prototype steel-framed building, for a seismic hazard representative of coastal California. The frame yield strength (based on M_y in Equation 2) was proportioned assuming a seismic response factor, so-called R-factor in United States practice, equal to 8, implying that the rocking frame has ductility comparable to other high-ductility systems.

The test setup for the quasi-static half-scale tests is shown in Figure 5.1, where the dual rocking frames are subjected to cyclic loads applied to the top of each frame. A total of nine tests were conducted, where the main variables investigated were alternative fuse types, variations in the self-centering ratio (M_{up}/M_{fsy} from Figure 2.3a), and dual versus single frame configuration. The hysteresis plots in Figure 5.1 illustrate the difference in response between thin and thick fuses, where the thin fuses initially have similar response to the thicker fuse but then degrade and pinch at large deformations, which improves self-centering relative to the thicker fuse. In addition to studying design variables, several of the quasi-static tests were run using hybrid simulation, where the restraining characteristics of the prototype building's gravity system and architectural partitions were modelled to investigate their effect on the self-centering tendency of the entire building system.

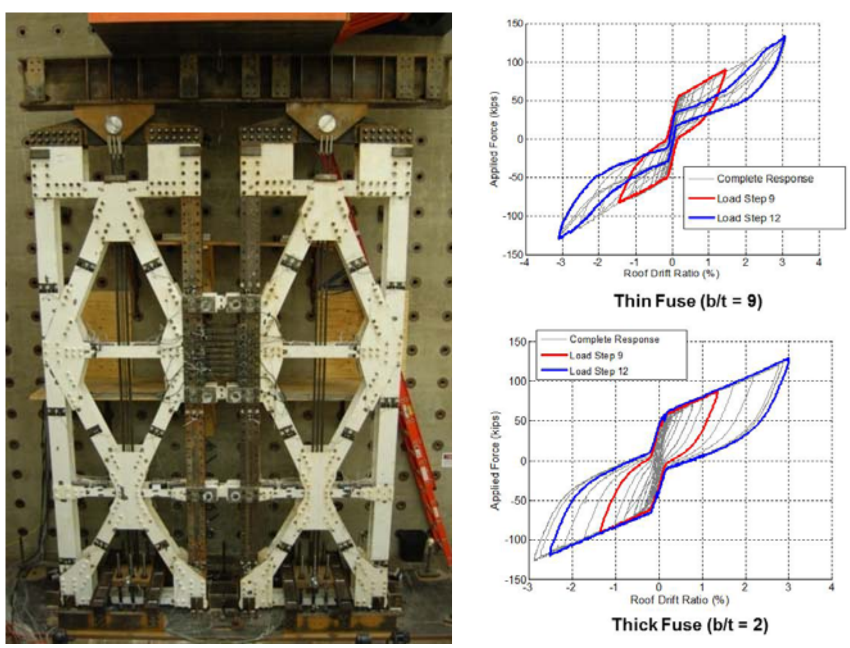


Figure 5.1 Test Setup at NEES Facility at University of Illinois and Results of a Quasi-Static Cyclic Test

The experimental setup for the shake table tests is shown in Figure 5.2, where the single rocking frame is sandwiched between two mass testbed units. A total of six tests were conducted under varying level ground motion intensities, up to and exceeding the "maximum considered earthquake" (MCE) intensity used as the basis of the frame design. The main variable investigated in the shaking table tests was alternative fuse characteristics, including one test where the butterfly fuse assembly was replaced by a single buckling restrained brace. The tests were conducted using the JMA record from the 1995 Kobe earthquake and the Canoga Park record from the 1994 Northridge Earthquake. Shown in Figure 5.3 is a representative test under an MCE ground motion, where the frame sustained over 2% story drift without any damage to the braced frame spine or the PT. The plot also illustrates the excellent agreement obtained between nonlinear structural analyses and the measured response. This agreement was attributed in large part to the fact that the well-controlled rocking and yielding mechanisms in the frames are generally straightforward to model.

Overall, both the quasi-static and shake table tests confirmed the expected behaviour and robustness of the rocking frames. The frames sustained drifts in excess of 3% story drift under MCE level ground motions without any yielding or damage to the PT tendons or the braced frame; the only damage at this intensity occurred to the fuses that were designed for easy replacement. Under higher ground motions, the PT tendons experienced yielding and fracture (a few cases), which diminished the self-centering capability but did not threaten collapse. The tests further validated the design, analysis, and construction procedures for the frames. For more complete details of the frame testing and analyses, the reader is referred to reports by Eatherton and Hajjar (2010) and Ma et al. (2011a).

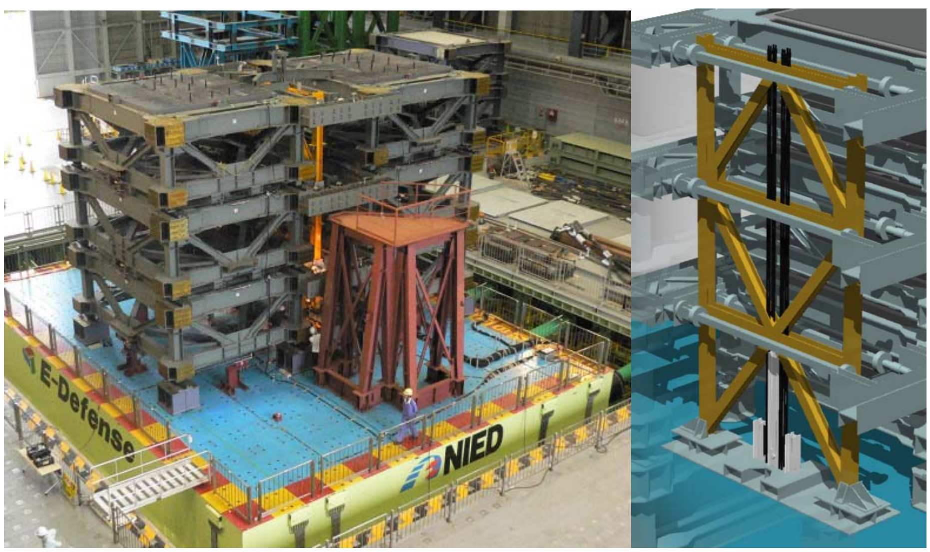


Figure 5.2 E-Defense Shaking Table Test of Three-Story Frame with Seismic Mass Testbed Simulator

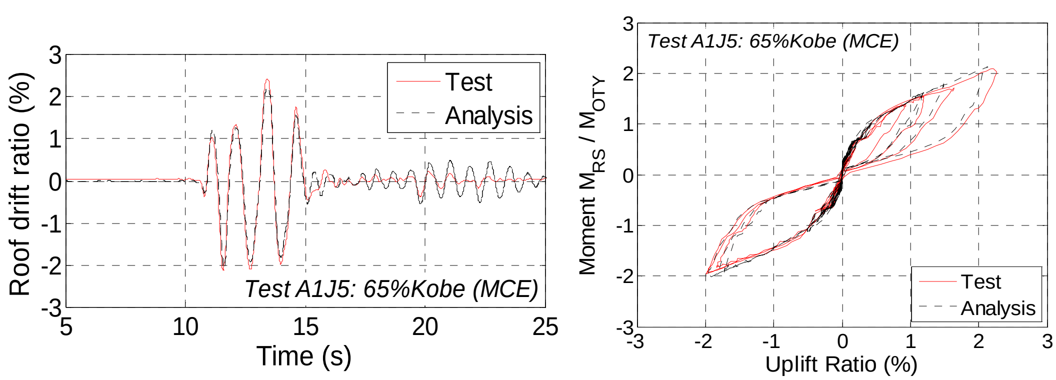


Figure 5.3 Shaking Table Results: JMA Kobe Motion Scale to MCE Intensity

6. LIMIT STATES AND PERFORMANCE BASED DESIGN CRITERIA

As illustrated in Figure 6.1, the idealized hysteretic system response under cyclic loading is influenced by several limit states in the PT and fuses. Implied in this response is that the rocking frame itself remains undamaged and maintains its integrity. Four key limit states, shown in Figure 6.1, are associated with (1) initial uplift, (2) fuse yielding, (3) PT yielding, and (4) PT and/or fuse fracture. Also note that frame uplift in post yield cycles will tend to occur at lower uplift moments, due to residual forces that develop in the yielded fuse.

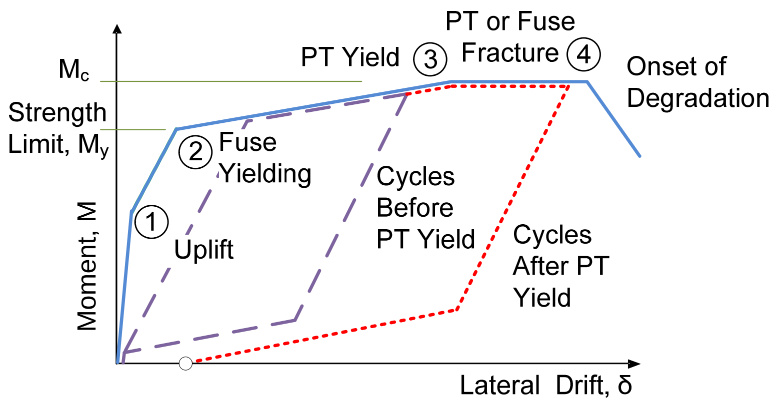


Figure 6.1. Limit States

The key design assumptions and limit state considerations for controlled rocking response are the following:

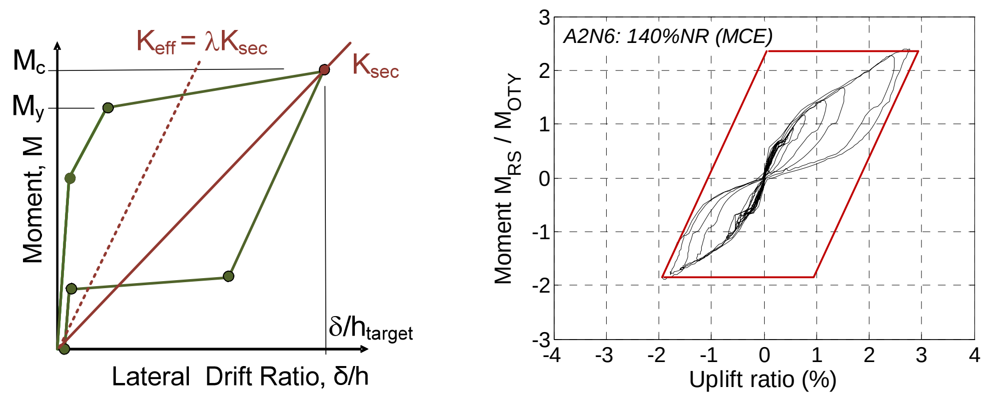
- The rocking braced frame should be designed to remain essentially elastic under the maximum forces developed under extreme (e.g., > MCE level) ground motions. As shown in Figure 6.1, the maximum base overturning resistance is limited by the fuse and PT strengths, although, the limit on maximum story shear forces is not as well bounded, depending on higher mode response in the frame.

- The initial uplift and yield strength should be large enough to minimize the onset of large drifts and damage to an acceptable ground motion intensity (return period). To achieve parity with existing systems, it is proposed to establish the nominal uplift/yield strength (M_y) based on the minimum design strength of other ductile seismic resisting systems, e.g., using an R-value equal to 8 in United States practice.

- The initial uplift/yield strength, hardening response, and energy dissipation capacity should be sufficient to control drifts under large (e.g., MCE level) ground motions. As shown in Figure 6.2a, the effective stiffness for calculating an effective vibration period and dynamic response of rocking systems can be estimated based on the secant stiffness to a target displacement. Since the maximum displacement varies with earthquake intensity, the effective stiffness will likewise vary. Studies by Ma et al. (2011b) suggest that an effective stiffness of about twice the secant stiffness provides reasonable predictions of inelastic drifts for target MCE drifts on the order of 0.02 to 0.04. Studies by Ma et al (2011b) and others also indicate that the drift will increase if the energy dissipation is significantly less than “conventional systems”. The ACI ITG (2007) guidelines for precast PT rocking walls specifies a minimum required energy dissipation for the rocking system of 1/8 (12.5%) of that for equivalent elastic-plastic systems, i.e., corresponding to the ratio of areas in the rocking hysteretic loops and the bounding elastic plastic loop shown in Figure 6.2b. The shaking table tests and analyses conducted in this research suggest that the minimum ratio should be about 20%. As a point of reference, the ratio of areas shown in Figure 6.2b is about 30%. Ultimately, the drift for a specified ground shaking intensity can be controlled by varying the sum of the PT and fuse strength and hardening (which affect the secant stiffness, Figure 6.2a) and the ratio of the initial PT to fuse strengths (which affect the damping ratio, Figure 6.2b).

- The PT and fuse should be proportioned to maintain self-centering action so as to minimize residual drifts up to the desired ground motion intensity (ground motion return period). Referring to point 3 in Figure 6.1, this implies that the onset of PT yielding should be controlled, since PT yielding is the primary factor in loss of self-centering. While pinching degradation of the fuse (e.g., Figure 5.1) will help to preserve self-centering, this may not be an effective way to compensate for PT yielding. Moreover, depending on the type of PT system used (7-wire strands versus high strength Dywidag bars), it is generally advisable to avoid yielding of PT at ground motions below MCE intensities.

- The PT and fuse should be proportioned and detailed to limit the onset of degradation (point 4 in Figure 6.1) due to PT and/or fuse fracture so as to maintain a sufficient collapse safety at MCE ground motions. Assuming that the rocking frame remains intact (essentially elastic), then fracture of the PT and fuses are the primary factors that can precipitate overturning and ultimately collapse of the rocking frame system. While our testing demonstrates that it is quite feasible to avoid fuse and PT fracture under MCE ground motions, this is a critical limit state that warrants careful quality assurance measures in design and construction.



(a) Effective Stiffness (b) Energy Dissipation Ratio

Figure 6.2 Dynamic Response Characteristics

7. CONCLUSIONS AND ONGOING WORK

Overall, the testing, analysis and design studies by the authors that are summarized in this paper demonstrate that steel braced frames with controlled rocking can provide reliable systems with enhanced performance over more conventional structural systems. The tests demonstrate that the rocking frames can sustain MCE level ground motions with drifts on the order of 2% to 3% without any structural damage, other than yielding of the replaceable fuses. Under larger motions, the frames performed reliably up to 4% drifts.

Continuing work is underway to further develop and validate design recommendations for self-centering elastic spine systems that employ controlled rocking, post-tensioning and energy dissipating fuses to resist large earthquake ground motions with minimal damage or residual drifts. These systems can be implemented using the steel rocking frame systems or alternative systems and materials, such as concrete shear wall systems or other steel spine geometries.

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