CONTROLLED ROCKING OF STEEL-FRAMED BUILDINGS WITH REPLACEABLE ENERGY-DISSIPATING FUSES

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ABSTRACT :

During a large earthquake, traditional seismic lateral resisting systems can experience significant damage distributed throughout the structural system, and residual drifts that make it difficult, if not financially unreasonable, to repair. A controlled rocking system has been devised which virtually eliminates residual drifts and concentrates the majority of structural damage in replaceable fuse elements. The controlled rocking system consists of three major components: 1) a stiff steel braced frame that remains virtually elastic, but is not tied down to the foundation and thus allowed to rock, 2) vertical post-tensioning strands that anchor the top of the frame down to the foundation, which brings the frame back to center, and 3) replaceable structural fuses that absorb seismic energy as the frames rock. This paper describes preliminary results from a half-scale test conducted at the University of Illinois at Urbana-Champaign. The experimental hysteretic response is compared to predictions made with a two-dimensional analytical model. The controlled rocking system exhibited excellent self-centering properties, and effectively concentrated the energy dissipation and structural damage in the replaceable fuse elements.

KEYWORDS: Controlled Rocking, Self-Centering, Flag-Shaped Hysteresis, Structural Fuses, Steel Buildings, Earthquake Resistance

1. INTRODUCTION

1.1. Need for the Controlled Rocking System

As structural engineers look toward performance based design as a way to quantify performance expectations and thereby enable owners to choose a desired level of performance, it becomes important for engineers to have higher performance systems to offer. Traditional seismic force resisting systems will often experience inelastic action throughout the structure during a large earthquake, which results in residual drifts and distributed damage that is difficult and costly to repair. Clients concerned about repairability after an earthquake, will want a structure that concentrates seismic damage in replaceable elements and one that does not exhibit residual drifts after an earthquake.

1.2 Self-Centering Systems for Steel Framed Buildings

Seismic force resisting systems that have the ability to absorb energy and also return to their original configuration after an earthquake are not common in steel-framed buildings. Several approaches, however, are being studied at institutions in the United States, Canada, Italy, Japan, Taiwan, and elsewhere. The approaches to self-centering a steel frame can be grouped into several categories. Self-centering braces have been designed and built using prestressed aramid fiber strands in conjunction with friction pads (Christopoulos et al. 2008), or shape memory alloys (Dolce and Cardone 2006; Zhu and Zhang 2008). Self-centering moment frames developed at Lehigh University (Ricles et al. 2001) and the University of California at San Diego (Christopoulos et al. 2002) consist of horizontally oriented post-tensioned bars or strands that hold a beam flush to a column until earthquake motions cause the beam to rotate relative to the column. Energy dissipation is implemented using yielding seat angles, friction dampers, or energy dissipating bars confined in tubes. Japanese researchers have investigated self-centering column bases that use post-tensioned bars (Ikenaga et al. 2006) or spring loaded wedges (Takamatsu et al. 2006). (Pekcan et al. 2000) studied a system with draped post-tensioned tendons with a non-rocking steel frame. The tendons spanned over multiple bays and multiple floors and used elastomeric spring dampers and fuse bars to provide energy dissipation.

Rocking of steel structures has been studied in a number of forms. Researchers in Japan have shown that yielding base plates that allow some uplift while dissipating energy can reduce the seismic response of moment frames and braced frames (Azuhata et al. 2006). Some researchers have implemented these yielding base plates at multiple locations along the height of braced frame columns (Wada et al. 2001).

U.S. and Taiwanese researchers have studied rocking of bridge piers (Pollino and Bruneau 2004; Chen et al. 2006). U.S. researchers used buckling restrained braces to dissipate seismic energy whereas the Taiwanese researchers studied free rocking. In both cases, gravity loads alone were relied upon for self-centering forces to overcome energy dissipation sources such as buckling restrained braces. In contrast to bridge systems, rocking frames for buildings rarely have enough gravity load for self-centering.

1.3 The Controlled Rocking System

With the goal to develop a seismic lateral resisting system for new construction that has post-earthquake self-centering ability and concentration of damage in replaceable elements, the steel braced-frame with controlled rocking system was developed. Figure 1 highlights one possible configuration of this system, which employs the following components:

1. Steel frames that remain essentially elastic and are allowed to rock about the column bases. As shown in Figure 1, the specially designed column base details permit column uplift and restrain horizontal motion by bumpers or an armored foundation trough. The configuration in Figure 1 uses two side-by-side frames, though alternative configurations with single frames are possible.
2. Vertical post-tensioning strands provide active self-centering forces. The strands are initially stressed to less than half of their ultimate strength, so as to permit additional elastic straining when the frames rock. The configuration in Figure 1 employs post-tensioning down the center of the frame; other configurations with strands oriented on the column lines are also feasible.
3. Replaceable energy dissipating elements act as structural fuses that yield, effectively limiting the forces imposed on the rest of the structure. In Figure 1, the fuses are configured as yielding shear elements between the two frames. Other configurations include fuses at the column bases or in inelastic vertical anchors. A number of different types of shear fuses were tested.

The controlled rocking system has a flag-shaped hysteretic response that is characteristic of self-centering systems. As shown in the left plot of Figure 2, the post-tensioning force creates a bilinear elastic response in the rocking frame, as the corner of the frame is allowed to uplift. As shown in the center plot, the fuse can be idealized as an elasto-plastic element with full hysteresis loops. The effect of combining the two elements is the flag-shaped hystersis loop shown on the right of Figure 2.

This paper briefly summarizes some of the early phases of this project, including tests on a range of fuse topologies to determine optimum fuse performance, and the results of the first of a number of half-scale system tests being conducted to test the complete structural system. In 2009, a series of two-dimensional, two-thirds scale shake table tests will then be conducted on the system at the E-Defense shake table facility in Miki, Japan.

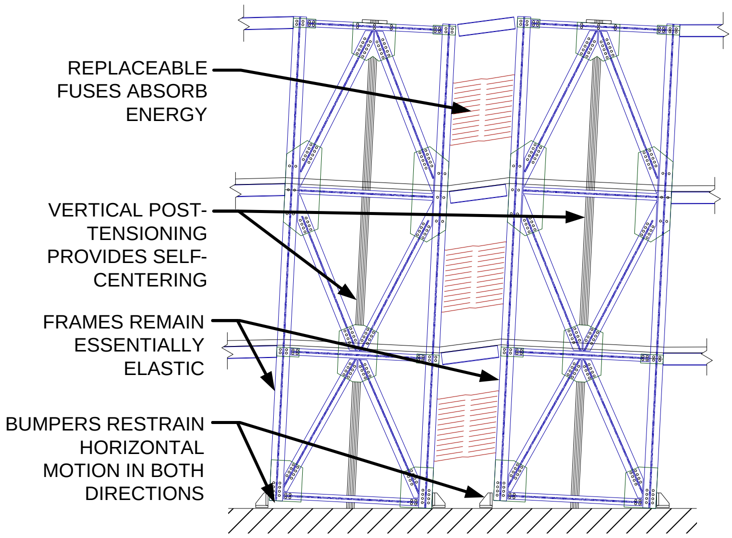

Figure 1 Controlled Rocking System (Left) and the Analytical Model Created In OpenSees (Right)

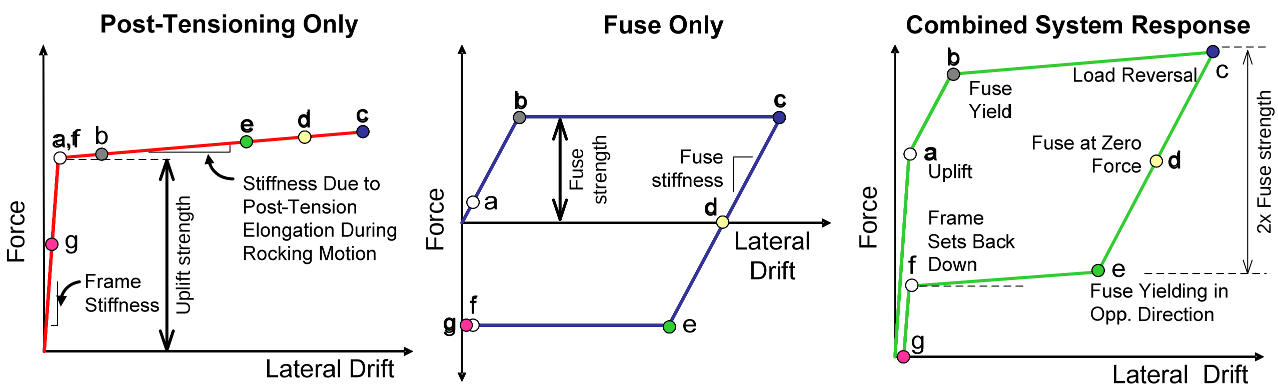

Figure 2 Schematic Depiction of the Controlled Rocking Hysteretic Response

2. TESTING PROGRAM

2.1 Fuse Tests

One of the key elements of the controlled rocking system is the replaceable energy dissipating fuse. The controlled rocking configuration shown in this paper utilizes a shear fuse panel. A testing program was conducted at Stanford University to design, test, optimize, and characterize replaceable shear fuse elements. Tested fuses employed high performance fiber reinforced cementitious composites, engineered cementitious composites, steel plates with straight slits, and steel plates with butterfly cut-outs. Eleven tests were conducted on fuses that represent approximately half-scale relative to the prototype building.

Through the course of the fuse testing program, fuse designs were optimized based on previous test experience. Figure 3 shows one of the tested fuses along with the resulting response. As demonstrated in the plot of the steel butterfly plate response, energy dissipating hysteresis loops can be obtained up to and exceeding shear strains of 25%. The fuse plate shown in Figure 3 is ¼” thick with seven tapered links designed to yield in bending at the quarter points before buckling and switching to more tension dominated response. The fuse plates are A36 steel and were cut using commercially available water jet technology.

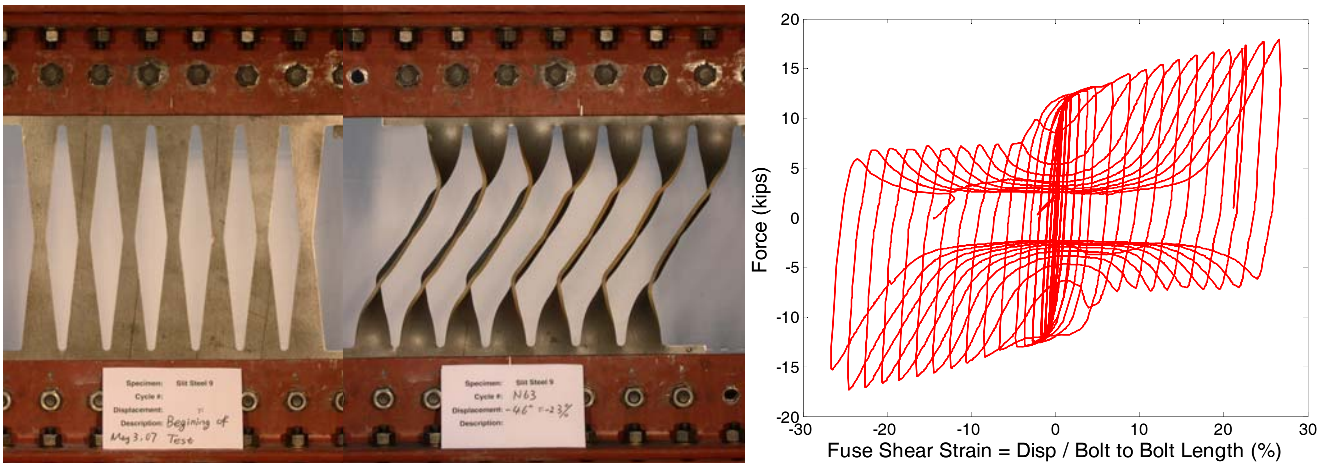

Figure 3 Undeformed Fuse (Left), Fuse at 23% Shear Strain (Middle), and Fuse Hysteretic Response (Right)

2.2 Half-Scale Quasi-Static System Tests

There are numerous goals for the experimental program conducted at the University of Illinois at Urbana-Champaign on half-scale specimens of the structural system including: 1) validate the system response, and examine fuse, post-tensioning, and rocking performance as part of the controlled rocking system; 2) investigate and improve details not common to steel structures such as rocking column bases and post-tensioning; 3) study force distributions in frame members, and changes in those distributions as damage progresses in the fuses; 4) provide detailed data for calibrating computational models; and 5) validate the repair and replacement characteristics of the system, as the same frames and post-tensioning will be reused in multiple tests.

A prototype three-story building was designed using controlled rocking frames assuming an arbitrary site in California and R=8. The test setup shown in Figure 4 represents an approximately half-scale version of the prototype frames, which is the first of eight tests that vary the primary system design variables including geometry, initial post-tension force, and fuse shear strength. The thickness and link geometry of the fuses are comparable to the one tested in an early phase of this work as shown in Figure 3. Struts were used above and below the fuses to help stabilize the columns when the fuses started to impose large tension forces on the columns. To accomplish the goals discussed above, extensive instrumentation, including strain gages, linear potentiometers, string potentiometers, LVDT's, load cells, inclinometers, and the Krypton 3D measurement system was used to monitor the deformations, strains, and loads experienced during the test. Still image photographs were taken at frequent intervals during the tests, and the experiment was videotaped using both high-speed and low-speed video.

The Loading and Boundary Condition Box (LBCB) at the UIUC NEES MUST-SIM facility was used to apply two-dimensional loading to the specimen while holding the out-of-plane displacement degrees of freedom constant. Two 7" diameter load cell pins transferred load from the LBCB into the two rocking frames (see Figure 4). The test control was designed to constrain the vertical load from the load cell pins to be zero in addition to directly controlling the horizontal string potentiometer readings at the roof level of the frames. The roof drift was controlled to follow a quasi-static cyclic displacement history designed to produce shear strains in the fuses equal to the targets outlined in Appendix S Loading Sequence for Link-to-Column Connections of the AISC *Seismic Provisions* (AISC, 2005). Figure 5 shows the roof drift ratio as well as the target fuse shear strains.

Figure 6 shows the geometry and member sizes of the controlled rocking frame specimen. Wide flange shapes were used in minor axis orientation as beams, columns, and braces, with gusset plates on the front and the back of the frame; it is intended that yielding in the frames be minimal during the tests. Eight standard ASTM A416 ½" diameter post-tensioning strands were used in each frame and were stressed to an initial pretension of approximately 30% of the strand ultimate strength. Fuses were cut from ¼" thick A36 steel plate with a yield strength of 38 ksi. Fuse links were ¾" wide at the center and taper to 2-1/4" wide at the ends.

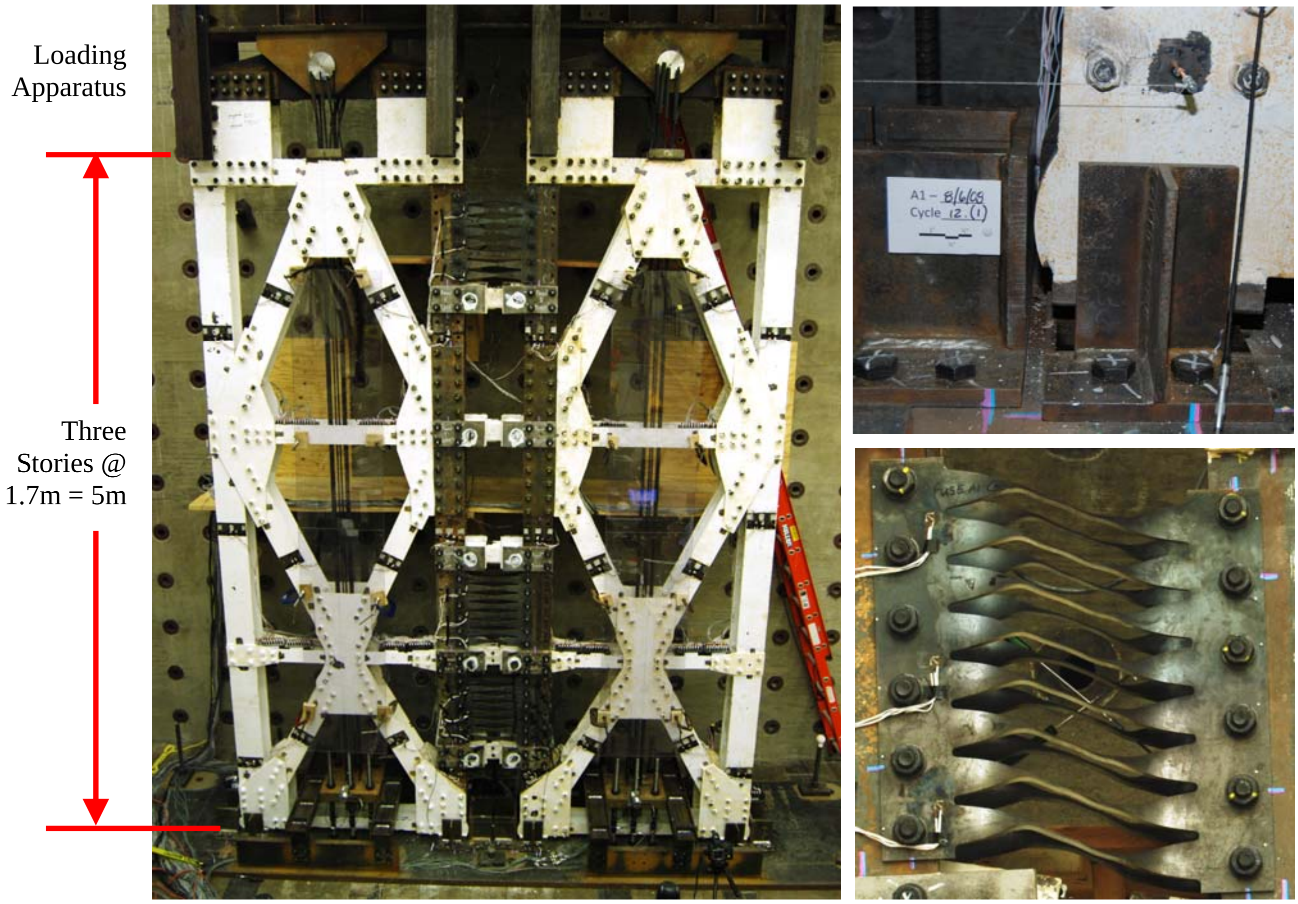

Figure 4 Half Scale Test Setup at UIUC (Left), Uplifted Base Connection (Top Right), Deformed Fuse (Bottom Right)

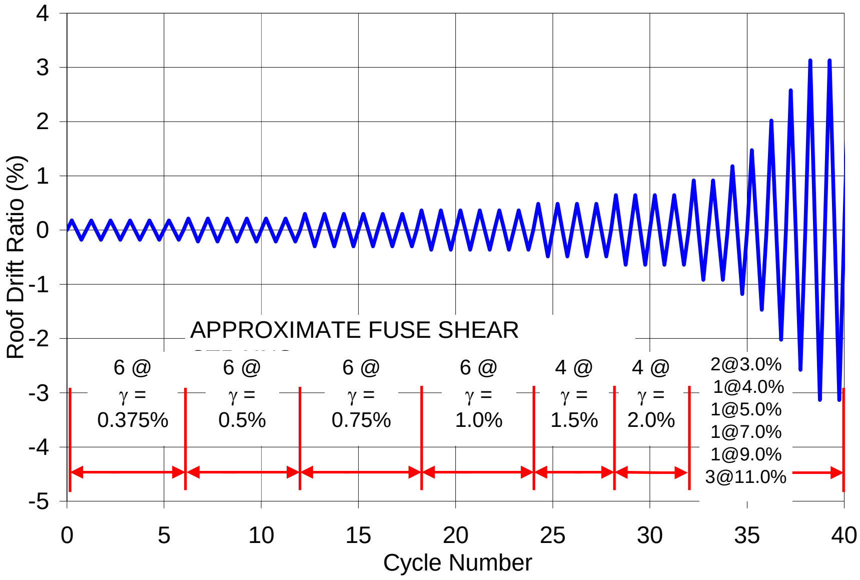

Figure 5 Displacement History Executed in Test A1

2.3 Computational Model of the Half-Scale Specimen

A two-dimensional frame model was created using the OpenSees Software to predict the response of the test specimen shown in Figure 4. Figure 6 shows a schematic representation of the computational model. Rocking motion at the base was simulated through springs that have high vertical stiffness in compression and zero stiffness in tension. Similarly, the elements representing the post-tensioning strands were modeled as pre-strained tension-only elements. The fuses were discretized using a component model that simulates the combined shear, moment, and tension experienced in the fuse during loading to large deformations. Rotational springs capture the plastic hinges that form in the fuse links while a hysteretic axial member captures the link's tension behavior after buckling. Frame members are designed to remain elastic and are thus modelled as elastic beam-column elements. The analysis and element formulation utilizes a large-displacement (co-rotational) formulation with nodal coordinate updating.

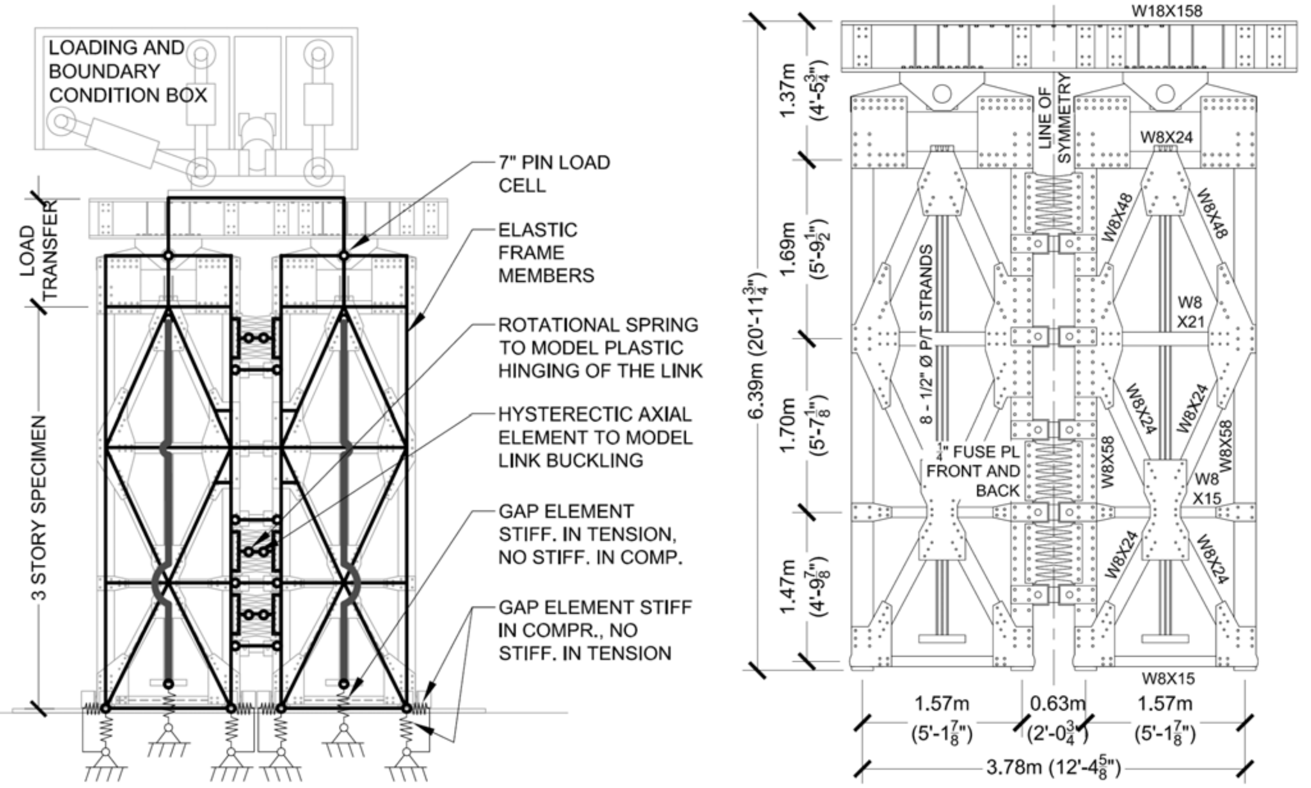

Figure 6 Schematic Representation of the OpenSees Analytical Model (Left) and Specimen Geometry (Right)

3. COMPARISON OF EXPERIMENTAL AND ANALYTICAL SYSTEM RESPONSE

Both the analytical model and the half-scale specimen were subjected to the displacement history shown in Figure 5. The hysteretic response of both are shown in Figure 7. Some observations include:

- The controlled rocking system demonstrated excellent energy dissipation coupled with self-centering characteristics. The residual drift was at most 0.2%. The residual drift that did exist was largely due to the tolerances used in between the bumpers and in the pin connections, and the residual drifts further reduced later in the loading history after the fuses had yielded inelastically. The fuses attained sustained cyclic shear strains of approximately 11%, less than one-half their anticipated ductility capacity, but sufficient to subject the system to more than 3% interstory drift.
- Differences are noted between the experimental response and the response predicted by the preliminary analytical model. The following reasons for the differences will be addressed in future analytical models:
    - The analytical model does not yet include strain hardening in the fuse elements; ancillary tests of the fuse materials exhibit significant strain hardening.
    - The analytical model does not yet fully capture the buckling of fuse links.
    - The tolerances between the bumpers and the frames were not included in the analytical model.

- The tolerances in the pin connections of the struts between the frames and the pin load cells were not included in the analytical model.
- The base rocking connections worked as planned in that there were no significant inelastic deformations.
- The vertical post-tensioning details successfully transferred the self-centering forces. There was some loss in post-tensioning force after the loading protocol because of seating loss. This will be investigated further to determine methods for mitigating this effect.

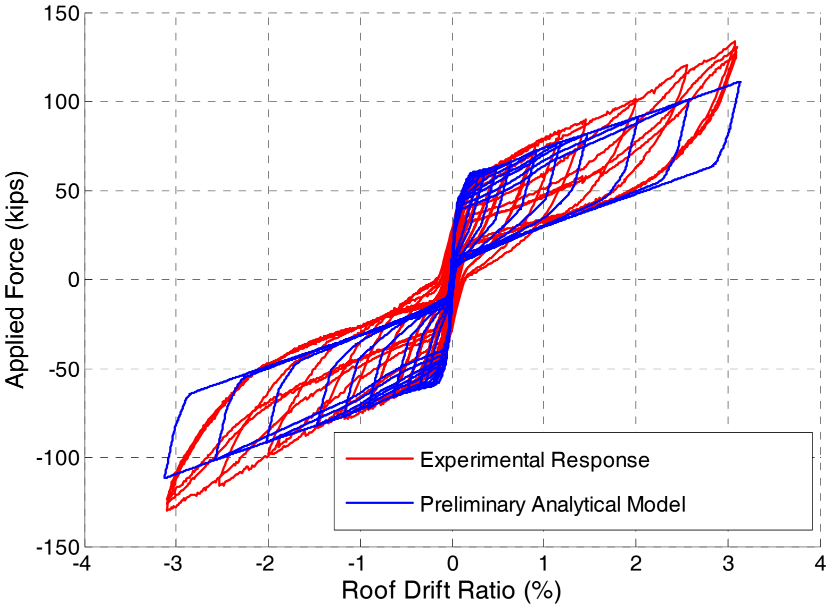

Figure 7 Comparison of the Experimental Results and the Preliminary Analytical Model

4. CONCLUSIONS

Traditional seismic resisting systems that rely on inelastic action in structural elements can result in residual drifts and distributed structural damage that is difficult and expensive to repair. A proposed alternative to this are self-centering rocking frame systems with replaceable fuses that are relatively easy to repair after an earthquake. The steel-braced frame controlled rocking system presented in this paper was shown to virtually eliminate residual drifts while concentrating structural damage in replaceable fuse elements. Computational and experimental studies have been carried out to identify and examine key design variables and demonstrate the viability of the system. The results described herein are preliminary and additional experimental and analytical investigation is forthcoming.

5. ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. (CMMI-0530756), the American Institute of Steel Construction, Stanford University, and the University of Illinois at Urbana-Champaign. In-kind funding was provided by Tefft Bridge and Iron of Tefft, Indiana, MC Detailers of Merrillville, Indiana, Munster Steel Co. Inc. of Munster, Indiana, Infra-Metals of Marseilles, Indiana, and Textron/Flexalloy Inc. Fastener Systems Division of Indianapolis, Indiana. The authors thank graduate students, Kerry Hall, Alejandro Pena, Eric Borchers, and Paul Cordova, practicing structural engineers, David Mar and Gregory Luth, and our Japanese collaborators for their contributions to this research. The LBCB Operations Manager and LBCB Plugin used in this research were developed by Narutoshi Nakata, Matt Eatherton, Oh Sung Kwon, Sung Jig Kim, and Curtis Holub with support from NEES@UIUC, Grant No. A6000 SBC NEES OMSA-2004, and the Mid-America Earthquake Center, NSF Grant No. EEC-9701785. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or other sponsors.

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