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LARGE-SCALE SHAKING TABLE TEST OF STEEL BRACED FRAME WITH CONTROLLED ROCKING AND ENERGY DISSIPATING FUSES

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ABSTRACT

Research and experience from past earthquakes suggest the need for buildings that are less vulnerable to damage and easier to repair after a major earthquake. Of particular concern are certain conventional systems, such as concentrically braced steel frame buildings, whose design may rely on more inelastic energy dissipation than the systems can provide. Our research aims to develop a new structural system that employs controlled frame rocking action and replaceable structural fuses to provide safe and cost effective resistance to earthquakes. The system combines desirable aspects of conventional steel-braced framing with energy dissipating shear fuses that are mobilized through rocking action. Vertical post-tensioning is provided to increase over-turning resistance and enhance the self-centering characteristics of the system. This paper describes the planning, design, and preliminary results of a two-thirds scale rocking braced frame tested on the E-Defense facility in Japan. The test specimen consists of a planar frame that was sandwiched between to “testbed” structures that supported the seismic mass and provided out-of-plane stability. Tests of the system under multiple ground motions and four alternative fuse designs demonstrate the robustness of the system to sustain ground motions in excess of the Maximum Considered Earthquake motions without damage.

Introduction

Traditionally, earthquake design requirements for buildings to resist earthquakes have focused primarily on life-safety (collapse prevention) and have not explicitly addressed damage control that is necessary to limit the risk of significant economic losses and building downtime after a major earthquake. As stated in the Uniform Building Code, “The purpose of the earthquake provisions herein is primarily to safeguard against major structural failures and loss of life, not to limit damage or maintain function (ICBO 1997)”. Whereas most engineers are

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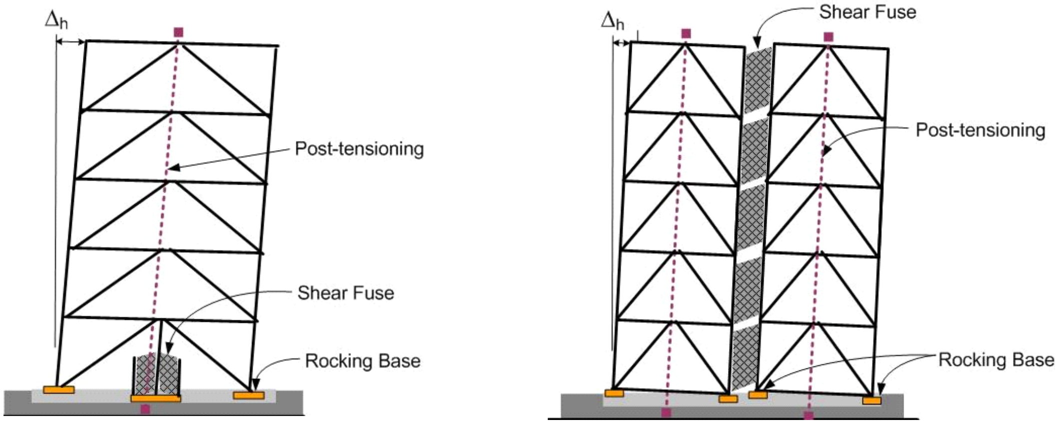
cognizant of this, typical owners and the general public are not aware of the level of damage that is likely to occur.

The objective of this project is to develop a new type of lateral force resisting system that provides significantly improved performance (reduction in damage, repair costs, and downtime) of buildings subjected to earthquakes. The specific design concepts to achieve the improved performance involve the development of a steel braced-frame system (Fig. 1) that employs controlled rocking action, active self-centering, and replaceable energy dissipating fuses to both minimize earthquake-induced damage and facilitate quick and economical post-earthquake repairs. When properly designed, the self-centering capabilities of the system will ensure that the system is structurally safe for continued occupancy after a large earthquake.

Controlled Rocking System



(a) (b)

Figure 1. Schematic of rocking frame configurations: (a) single frame, and (b) dual frame.

In concept, there are multiple ways to implement controlled rocking systems using alternative configurations and materials. Shown in Fig. 1 are two alternative frame configurations that we are investigating. In both configurations, the key components of the system are (a) steel-braced frames, (b) vertical post-tensioning (PT) strands, and (c) replaceable fuses. The braced frames and post-tensioning are designed to remain elastic, while the frame rocks on its base and dissipates energy in the replaceable fuse. In the single frame configuration the energy dissipating fuses are located in the center of the frame, coincident with the post-tensioning. In the dual frame configuration, the shear fuses are located between the two frames. The single frame has the advantage of simplicity, since fewer components are required. The dual frame has the advantage that the configuration amplifies the deformations in the shear fuses, thereby providing greater mobilization of the fuses at low drifts.

As shown in Fig. 2, the overall load-deflection behavior of the combined rocking frame system is based on superposition of strength and restoring actions of the rocking frame with post-tensioning (PT) tendons and the fuse system. The post-tensioned frame exhibits nonlinear elastic response, where the uplift strength and restoring force is controlled by the stresses in the PT plus any gravity loads acting on the frame. The PT strength (at uplift) is proportional to the initial force in the PT strands and the effective over-turning bay dimension of the rocking frame. The fuse system provides energy dissipation through elastic-plastic hysteretic response, although the shape of the hysteresis loop will depend on the specific characteristics of the fuse. The lateral strength provided by the fuse system depends on the fuse strength and the frame geometry. Combined, the two mechanisms result in the “flag shaped” hysteresis loop, where the self-centering ability depends on the difference between the restoring PT force and the fuse strength.

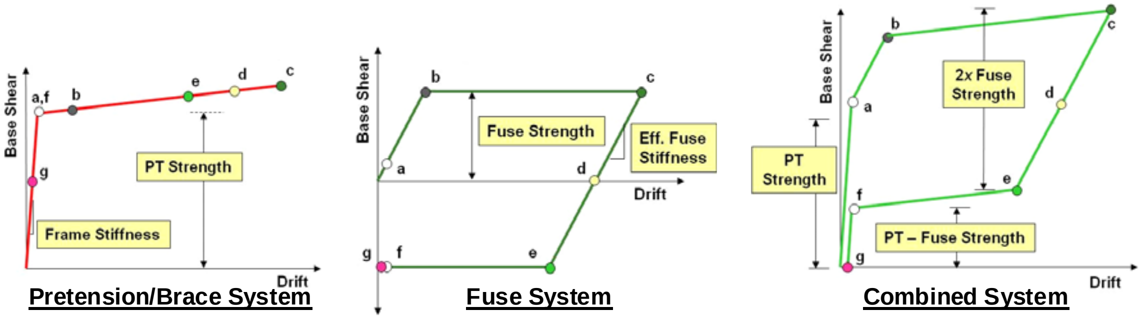


Figure 2. Load-deflection behavior of rocking frame system.

Energy Dissipating Fuses

The fuse components should be designed with sufficient ductility and toughness that they can dissipate energy throughout the cyclic loading expected during large earthquakes. Moreover, the fuses should be detailed to permit easy replacement in the event they become damaged. Finally, to help ensure self-centering of the frame after large earthquakes, it is desirable (though not essential) that the fuses exhibit some limited degradation under large deformations.

After considering several alternatives, the authors developed a fuse that consists of a steel plate with “butterfly” shaped links. An example of a fuse that was tested at Stanford University as part of this research is shown in Fig. 3. This fuse was fabricated, using standard water-jet cutting, from a thin (6 mm thick) steel plate. For the initial loading region, up to about 7% shear distortion in this example, the fuse links resisted shear force through flexural action with fat hysteresis loops. Beyond deformations of about 7% shear distortion, the links began to buckle in a torsional-flexural mode. At this stage, the flexural resistance of the links decreases and the links begin to resist forces through tension field action. Upon load reversal, the hysteresis loops

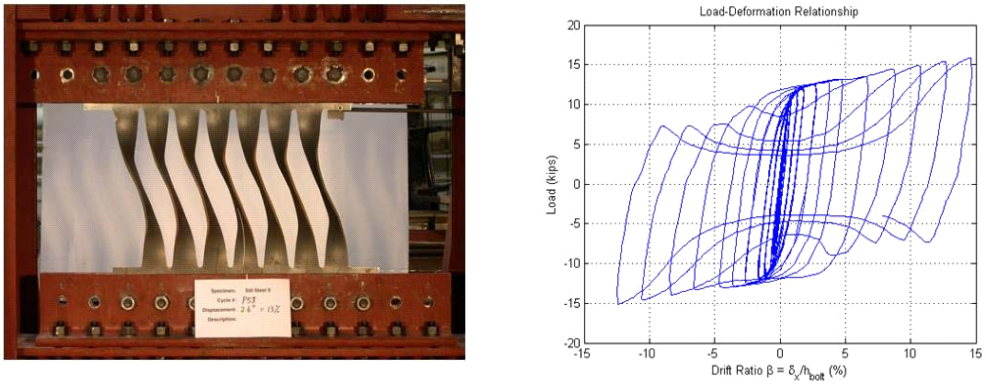
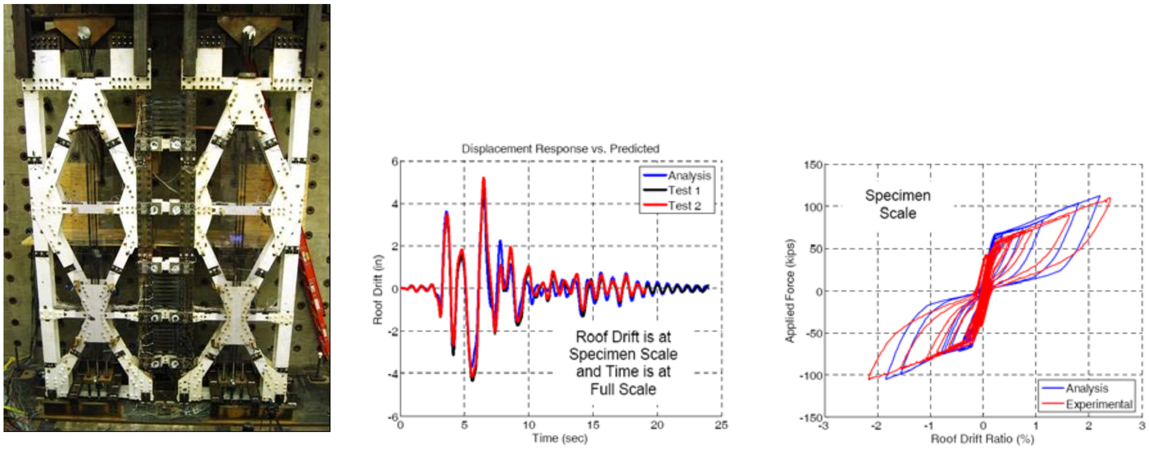


Figure 3. Energy dissipating shear fuse test specimen

become pinched as the links buckle in compression and then pick up force again as they stretch in tension. While the pinching decreases the amount of energy dissipated at each cycle, the drop in resistance at large deformations tends to improve the self-centering characteristics of the rocking frame. The degradation in fuse strength also helps to protect the other portions of the rocking frame that are designed to remain elastic under large earthquakes. In this sense, the fuse become sacrificial elements, designed for replacement following a large earthquake.

Dual Frame Tests

With the goal to investigate the rocking frame behavior and associated design details, we have recently completed tests of a large (1/2 scale) three-story rocking frame specimen at the University of Illinois NEES facility (Eatherton 2009). Shown in Fig. 4a is a photograph of the rocking frame specimen. This specimen is based on the dual frame configuration (Fig. 1b). In total, seven tests were conducted on the frame to examine alternative fuse designs, varying post-tensioning force, and alternative loading histories – including tests that utilized hybrid simulation to combine the physical test frame with a computational model of the prototype building systems.



(a) (b) (c)

Figure 4. Dual-frame test specimen: (a) photograph, (b) time-history response, and (c) load-deflection response

The test specimen was designed based on a prototype three story office building designed for a typical high seismic site in Los Angeles, California. Based on the design spectrum (characterized by a short period spectral acceleration of S_{DS}=1g and one-second period of S_{1S}=0.6g) and using a seismic response modification factor of R=8 (typical in the U.S. for ductile force resisting systems), the minimum required design base shear coefficient (V/W) for the frame is 0.125. This base shear was used to establish the minimum required strength of the rocking frame, corresponding to the point "b" in the response plot for the combined system in Fig. 2. This strength is equal to the overturning resistance provided by the initial PT force (typically on the order of 30% to 50% of the nominal tensile strength of the PT tendons) combined with the nominal yield strength of the shear fuse. The required base shear, calculated using R=8, is about 25% less than for a conventional braced frame.

Shown in Figs.4b and 4c are summary data from one of the rocking frame tests that was loaded pseudo-dynamically under the JMA Kobe record. Included in the figure are pre-tests analyses along with the measured response. The results shown are for loading of 1.1 times the recorded JMA Kobe ground motion, which has spectral intensities about 2.4 times larger than the Design Basis Earthquake (DBE) and 1.6 times larger than the Maximum Considered Earthquake (MCE). It is quite remarkable that even at this high intensity, the maximum drift ratio was limited to about 2.3% and the frame experienced no residual drift. Moreover, there was very limited damage to the fuse and little loss in PT force. Owing to the limited damage under the extreme ground motion and to further demonstrate the reliability of the response, the frame was subsequently subjected to (and survived without significant damage) a second loading with the 1.1 JMA Kobe record.

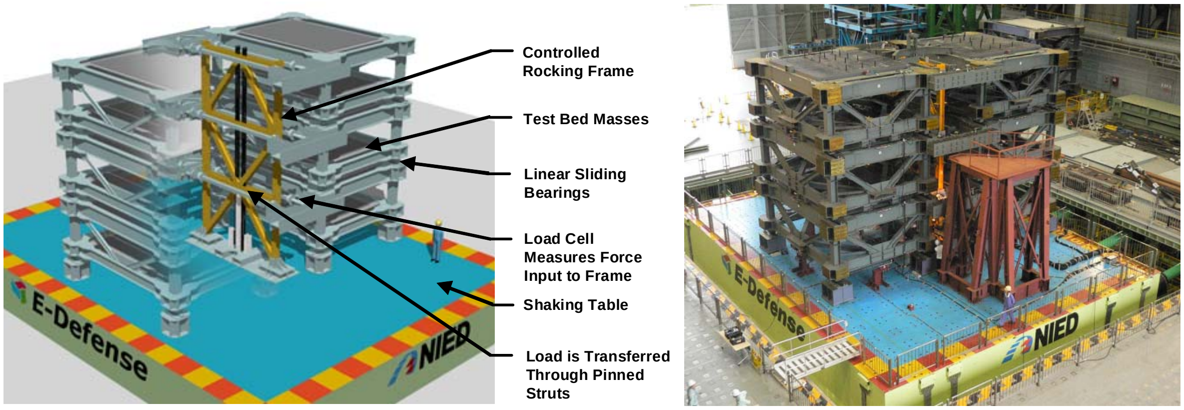
The agreement between the analysis and measured data in Figs. 4b and 4c demonstrate that the response can be accurately predicted with nonlinear analysis models. As the primary yielding element is the shear fuse, accurate modeling can be achieved provided that the shear fuse model is calibrated to the shear fuse response (Fig. 3). The slightly pinched hysteretic response in Fig. 4c reflects the slight degradation of the fuse at large deformations.

Shaking Table Tests

To further examine the performance of the controlled rocking frame system, a large (2/3) scale three-story frame was tested at the E-Defense facility in Miki, Japan. The test was jointly conducted with a team from Stanford University, the University of Illinois, Tokyo Institute of Technology, Hokkaido University, and E-Defense.

Test Setup

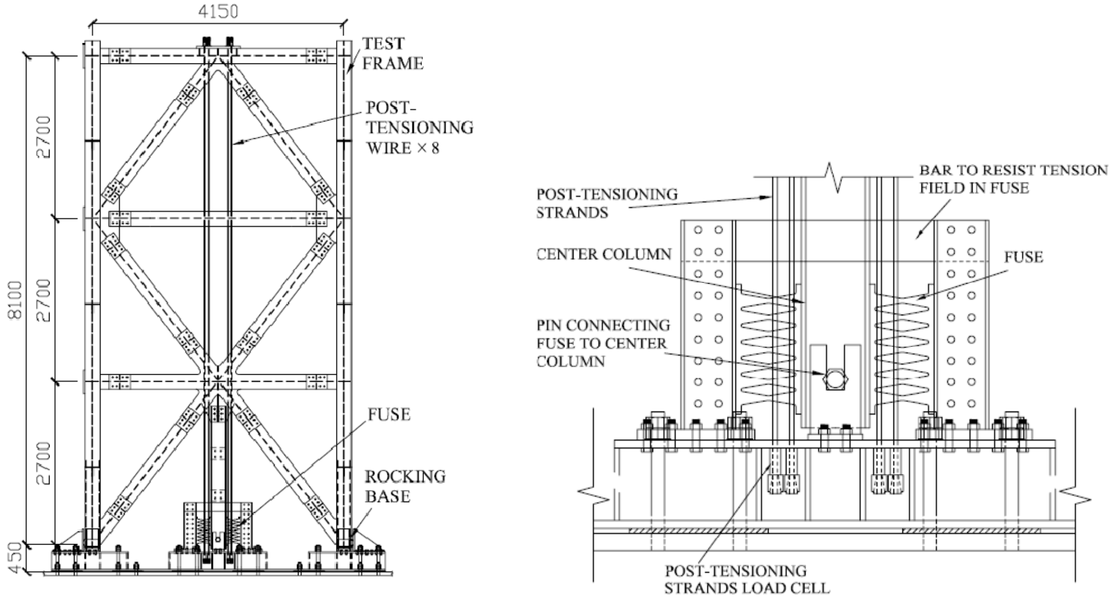
As shown in Fig. 5a, the shaking table specimen is based on a single rocking frame configuration, where the post-tensioning and fuse are located along the centerline of the frame. The frame is designed for a similar prototype building and design criteria as described previously for the dual-frame configuration tests. The frame tests utilize a re-usable testbed assembly (shown in grey in Fig. 5) that provides the inertial mass and bracing for out-of-plane stability



(a) (b)

Figure 5. E-Defense shake table test setup: (a) schematic of the setup and (b) photograph.

(Takeuchi et al., 2008). This re-useable testbed offers significant savings in the required time, budget and complexity of the rocking frame tests. Details of the braced frame and fuse assembly are shown in Fig. 6.



(a) (b)

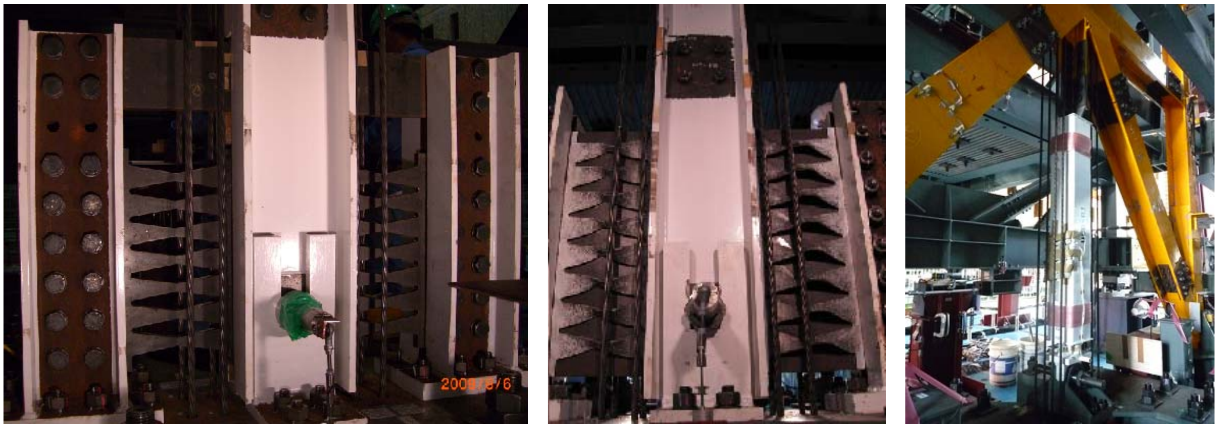
Figure 6. Specimen drawing: (a) braced frame and (b) fuse assembly.

Test Matrix

As summarized in Table 1, four tests of the rocking frame were conducted to investigate alternative fuse designs and effect of different ground motion inputs. The three types of fuses are shown in Fig. 7. Photo of the degrading fuse was taken after the B test when the fuse links had already experienced significant buckling. During each test, the specimen was subjected to multiple shakings with varying degrees of intensity. The scale factors are determined by matching the acceleration spectra of the original ground motions with the design spectra over a range of periods from 0.3 sec to 2.0 sec. This range represents the periods a rocking frame is likely to experience due to nonlinear behavior after uplifting.

Table 1. Test Matrix

Test ID	Fuse	Ground Motions	Motion Intensity
A1	Non-degrading Butterfly Fuse	JMA Kobe NS	30%~65% (MCE)
A2	Non-degrading Butterfly Fuse	Northridge Canoga Park	25% ~ 140% (MCE), 175%
B	Degrading Butterfly Fuse	JMA Kobe NS	10%~60%
C	Buckling Restrained Brace	JMA Kobe NS	10%~65% (MCE)

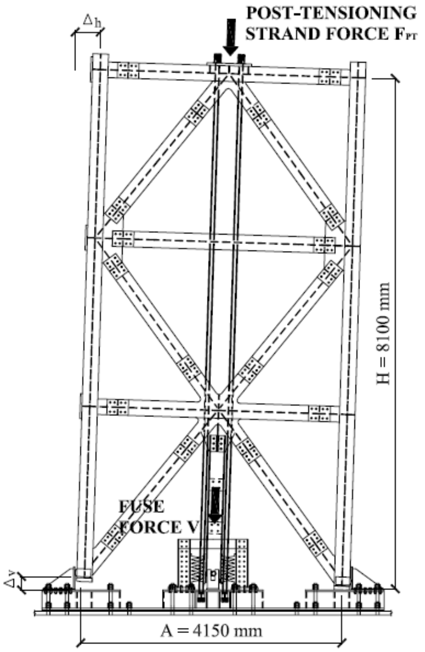


(a) (b) (c)

Figure 7. Fuse assemblies: (a) test A1 and A2 with non-degrading fuse, (b) test B with degrading fuse, and (c) test C with buckling-restrained brace.

Test Results

Some highlights of the findings are presented in this paper, while a comprehensive analysis of the test results is still underway. The system response can be characterized by roof drift ratio, uplift ratio and restoring moment which are defined in Fig. 8.



Roof drift ratio

$$RDR = \frac{\Delta_h}{H}$$

Uplift ratio

$$ULR = \frac{\Delta_v}{A}$$

Restoring moment

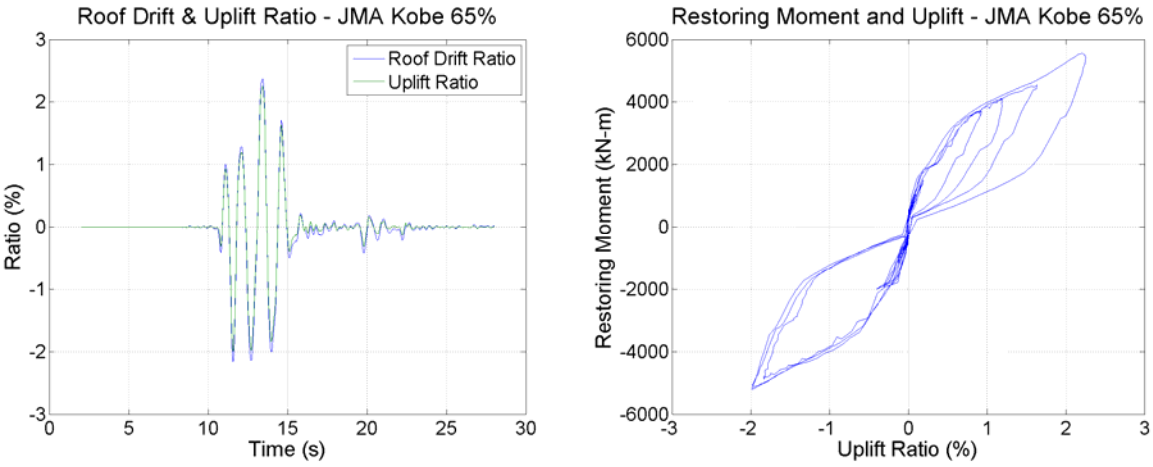
$$M_{rs} = (F_{PT} + V)A/2$$

Figure 8. Definition of key response parameters.

Overall System Behavior

The result from a shaking in test A1 with MCE level ground motion is shown in Fig. 9. The time-history of roof drift and uplift ratios shows almost identical response, which indicates the frame was primarily undergoing rigid rotation during rocking. The maximum RDR is about 2.4%. From the perspective of structural damage, such magnitude of deflection might be considered large for a conventional braced frame. However, it doesn't necessarily warrant the same level of concerns for the rocking frame system, because the deflection almost entirely came from rigid-body motion. Strain gage readings confirmed that the frame members remained elastic during the test.

The "flag shaped" system load-deflection hysteresis, discussed in previous section (Fig. 2), is evidenced by the test result in Fig. 9b. The loops resulted from energy dissipating function of the fuse, and the curve's returning to the origin illustrates the self-centering capability of the system. The zigzags at the mid-height of each loop are due to slip that occurred at the fuse pin connection. For installation purpose, the pin holes in the fuse and center column were made about 1 mm larger in diameter than the pin, which resulted in slippage every time before the pin hit the fuse from either direction.



(a) (b)

Figure 9. Overall system behavior from test A1: (a) time-history of roof drift ratio and uplift ratio, (b) restoring moment and uplift ratio hysteresis.

Fuse Behavior

The effect of different fuses is examined by comparing the response from test A1, B and C. Given the same ground motion input, it is found non-degrading fuse and BRB led to almost identical system behavior in terms of uplift ratio time-history, whereas the degrading fuse tends to cause higher response. For instance, with 55% JMA Kobe input, specimen with non-degrading fuse and BRB had a maximum uplift ratio of 1.8% and 1.7% respectively, whereas specimen with degrading fuse had 2.2% uplift. Such difference shows that fuse has notable influence on the system's response. Moreover, non-grading fuse is almost equally effective as BRB in limiting the frame's maximum uplift.

Ground Motions

Comparison between A1 and A2 demonstrates that even scaled to the same level according to the same scaling rule, different ground motions may lead to very different response. The maximum uplift ratios from test with MCE level JMA NS and Northridge ground motions are 2.3% and 2.8% respectively. Further investigation of the scaling rule and ground motion characteristics is underway to understand this difference.

Numerical Analysis

Before the tests, a 2D model was built using the program OpenSees to perform FEM analysis of the system. Fig. 10 illustrates key features of the model. Compression only springs are defined at the base allowing free uplifting of the frame. Butterfly fuse links are represented by beam and rotational spring elements with equivalent axial and bending capacities. The testbed is modeled by lumped masses on three nodes that are constrained to move horizontally. Springs are placed between the mass nodes to simulate friction in the linear sliders between testbed units, and 0.5% Rayleigh damping is assumed. The model is relatively simple and takes about 2 minutes to run the analysis of one shaking.

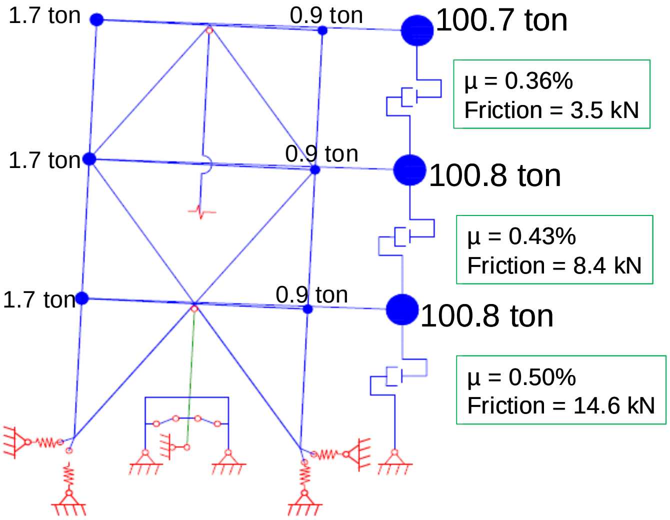


Figure 10. OpenSees model of the specimen.

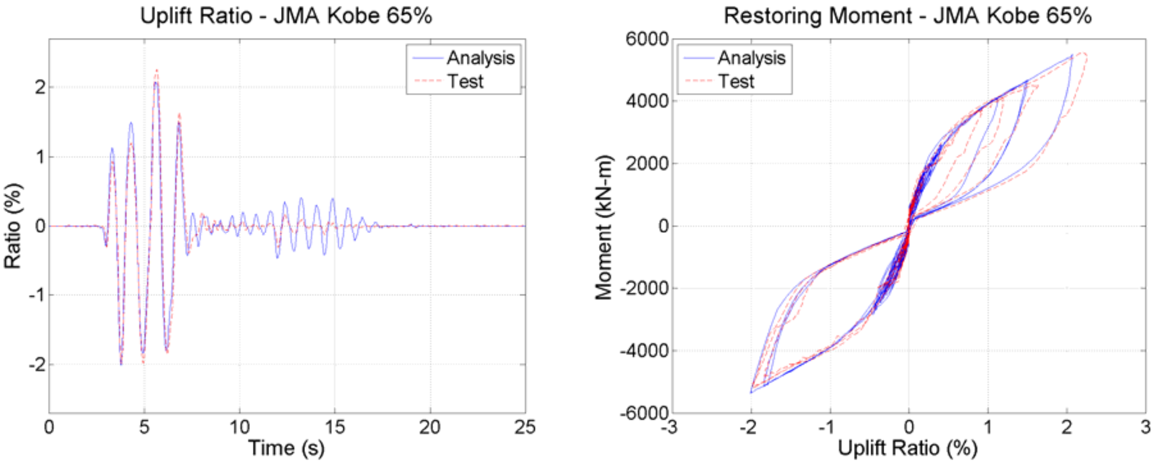
Results from pre-test analysis and actual test of a shaking in test A1are compared in Fig. 11. Overall the analysis gives reasonably close prediction of test response. The difference in maximum response is less than 10%. Such agreement is also found in the simulation of most of the other tests. One notable difference between analysis and test, however, is observed in the uplift ratio time-history after 10 sec. In the test the response quickly damped out, while the analysis has a few more cycles of rocking before the frame completely settles down. Modeling of damping is being examined to further investigate the difference.

Conclusions

Research on the controlled rocking frame system was presented in this paper. Emphasis was given to the E-Defense shaking table test of the system. The following conclusions are drawn from preliminary analysis of the test result.

(1) Design criteria and constructability of the system were exercised and validated.

(2) Key performance characteristics of the controlled rocking system such as self-centering, column base rocking, and damage control and reusability were verified through the tests.
(3) A relatively simple FEM model was shown to be accurate for predicting the behavior up to story drift ratios of 3%.
(4) Work is ongoing to fully process the shake table test data for the purpose of establishing a consistent seismic design methodology for the system.



(a) (b)

Figure 11. Comparison of analysis and test result from A1: (a) time-history of uplift ratio, (b) restoring moment and uplift ratio hysteresis.

Acknowledgments

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