

# Experimental and Analytical Study of Seismically Isolated Structures with Uplift Prevention

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## Summary

*Experimental and analytical studies of a seismically isolated five-story model structure are conducted to understand the behavior of a novel uplift-prevention Friction Pendulum isolator. Shake table testing on the earthquake simulator at the University at Buffalo involves a number of simulated ground motions with a variety of frequency content and amplitude. A comprehensive analytical model is developed to predict the dynamic response of the model structure. The computer program 3D-BASIS-ME is enhanced to include an element representative of the mechanical behavior of the new isolator and used for comparison with experimental results. The experimental results generated demonstrate the effectiveness of the new isolator in uplift prevention and provide satisfactory evidence for the validity of the new element incorporated in 3D-BASIS-ME.*

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## Introduction

With its appealing conceptual simplicity and its proven effectiveness, seismic isolation has become the epitome of seismic-resistant engineering in recent years. Having found a plethora of applications in many parts of the world over the past couple of decades, seismic isolation has emerged as a pragmatic approach to providing earthquake resistance to structural systems.

The fundamental strategy underlying the seismic isolation technique involves decoupling the structure from the damaging horizontal ground motion, by means of additional flexibility and energy dissipation capability, thus mitigating structural vibration and damage during seismic events.

Research developments in the areas of analytical modeling and experimental validation techniques have been paralleled by notable advances in seismic isolation device hardware. Advocated herein is a novel uplift-prevention Friction Pendulum isolator, abbreviated hereafter as XY-FP. While a conventional Friction Pendulum in principle (Zayas et al., 1987; Mokha et al., 1990; Constantinou et al., 1993), the proposed isolator is morphed into two perpendicular opposing concave beams. Furthermore, the configuration through which the two parts are interconnected permits tension to develop in the bearing, thereby preventing uplift in case of large overturning moments.

This paper presents an experimental and analytical study on seismic isolation of a five-story frame building with large overturning effects incorporating the new XY-FP isolator. The objectives of this study are to: (a) generate experimental results that demonstrate the effectiveness of the XY-FP

isolator in uplift prevention; (b) modify the computer program 3D-BASIS-ME (Tsopelas et al., 1994) to include an element representative of the mechanical behavior of the new isolator; and (c) assess the validity and accuracy of analytical methods to predict the behavior of such systems.

### Model Description

The shake-table testing on the earthquake simulator at the University at Buffalo involved a five-story single-bay moment-resisting steel frame. A schematic and a photograph of the quarter-scale model structure are illustrated in Figure 1. The structure is square in plan with a dimension of 52 inches. The story heights are 43 inches for the first story and 47 inches for the remaining stories, for a total height of 231 inches. The member layout is identical for all stories. The floors are comprised of MC 6x12 channel sections. In conforming to the similitude laws, artificial mass, in the form of steel plates and lead blocks, was added to the structure at all floor levels. The structure was mounted on a 6.9-kip steel plate, for a total weight of 24 kips.

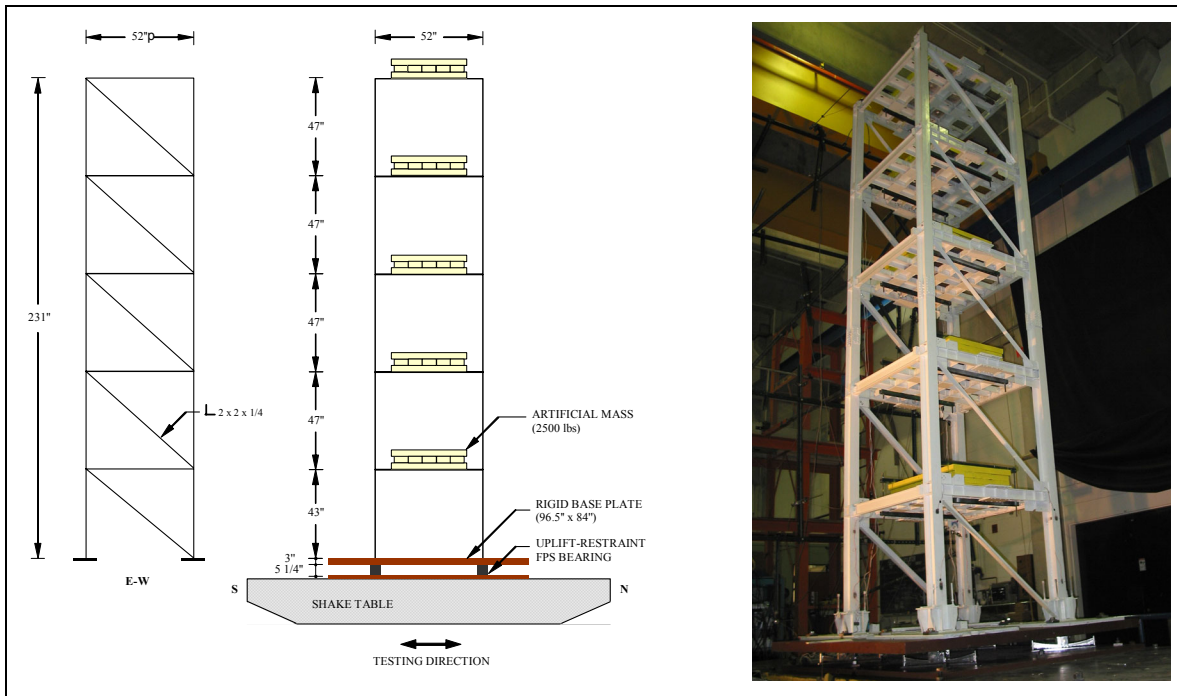


Figure 1. Seismically isolated five-story model on seismic simulator of the University at Buffalo

Installed beneath the base plate, the isolation system is comprised of four XY-FP bearings. While a conventional Friction Pendulum in principle, the XY-FP bearing consists of two perpendicular stainless steel concave beams with their concave surfaces opposing each other (Figure 2). Under the imposed constraint to remain mutually perpendicular, the two beams can move independently relative to each other. Furthermore, the configuration through which the two parts are interconnected permits tension to develop in the bearing, thereby preventing uplift in case of large overturning moments. The isolator at hand has a radius of curvature of 39 inches and is designed to have a displacement capacity of 8 inches.

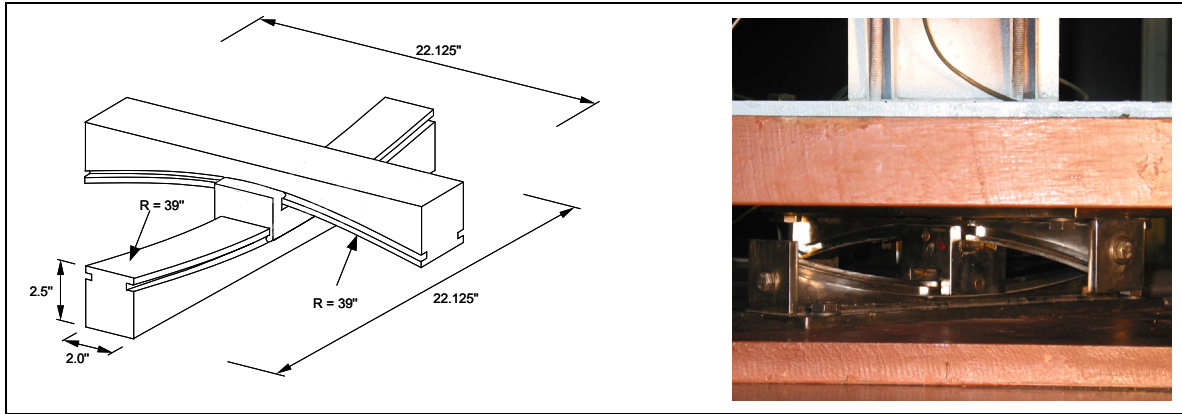


Figure 2. Uplift-prevention XY-FP bearing

## Testing Program

The shake-table testing on the earthquake simulator at the University at Buffalo utilized the slender five-story model structure described above. The testing program involved a number of simulated ground motions having a variety of frequency content and amplitude. Each record was compressed in time by a factor of two to conform to similitude requirements. The bearings were rotated below the base plate for testing in different directions. Specifically, tests were done at 0-degree, 45-degree, and 90-degree angle of bottom bearing beam with respect to the excitation direction.

The instrumentation of the five-story model structure consisted of accelerometers and displacement transducers which recorded, respectively, the horizontal accelerations and displacements of the frame at floor levels, the base plate, and the shake table. In addition, the first-story columns were calibrated with strain gauge load cells to measure the first-story shear. To assess the accuracy of important recordings, measurements were contrasted with corresponding calculated quantities. For instance, to check the direct acceleration measurements, recorded floor absolute displacements were double-differentiated to obtain floor acceleration histories. In addition, first-story shear was calculated by summing up floor inertia forces (product of floor mass and floor acceleration) and compared to the recorded first-story shear.

## Analytical Prediction of Response

A comprehensive analytical model has been developed to predict the dynamic response of the model structure. The computer program 3D-BASIS-ME (Tsopelas et al., 1994) has been enhanced and used for comparison with experimental results.

Assumed to remain elastic at all times, the five-story superstructure model in 3D-BASIS-ME utilized the shear-type representation. Each floor mass is lumped into a single point mass having three degrees of freedom (two lateral and one torsional) in the horizontal plane. The isolation system was modeled with spatial distribution and explicit nonlinear force-displacement characteristics of the individual isolation devices. To accommodate the mechanical behavior of the new XY-FP isolator, a new hysteretic element (TYPE8) was incorporated into the program. Contrary to the conventional FP isolator (TYPE6), the new element is capable of providing uplift prevention.

The analysis accounted for: (a) the variability of axial load in isolators due to overturning moment effects; (b) the dependency of friction on velocity (Constantinou et al., 1990); (c) the dependency of friction parameter  $f_{max}$  on bearing pressure (Constantinou et al., 1993); and (d) the initial displacement of the isolators, namely the permanent displacement from the immediate previous test.

### Comparison of Analytical and Experimental Results

The validity of the 3D-BASIS model, especially with reference to the newly introduced XY-FP isolators, was investigated by comparison of the analytical predictions with experimental results.

Figure 3 depicts a comparison between experimental and analytical results for bearing direction of 45 degrees with respect to the excitation direction for two input ground motions. The comparison was made in terms of histories of the isolation system displacement, the first-story shear, and the bearing axial force, as well as in terms of shear force-displacement loops for the isolation system. The presented experimental results attest to the accuracy of the analytical model incorporated in 3D-BASIS-ME.

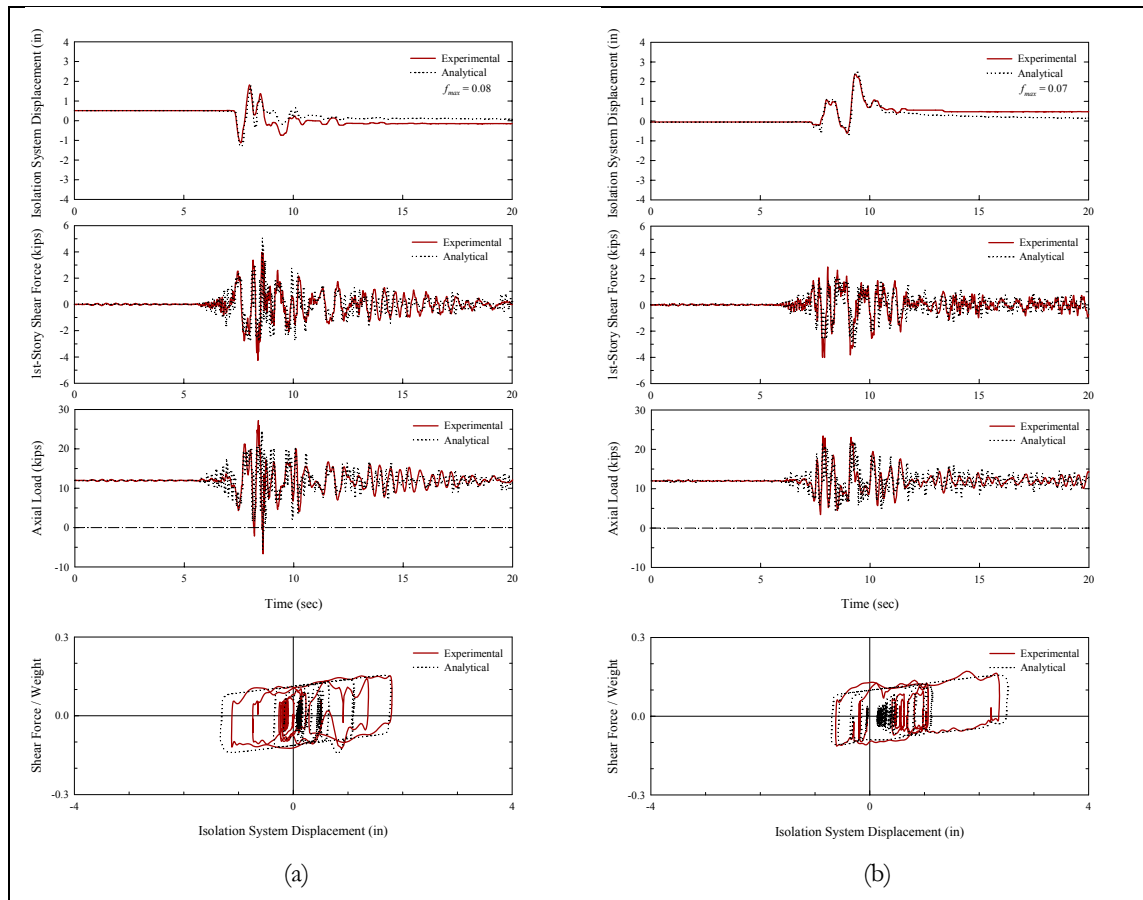


Figure 3. Comparison between experimental and analytical results for (a) Newhall 360, and (b) Sylmar 90 excitation.

Of particular interest are the axial force histories associated with the isolators, herein plotted per isolator pair. Due to the slenderness of the structure (height to width aspect ratio approximately 4.5), large overturning moment effects were induced on the bearings under strong lateral shaking. For the most severe motions, the fluctuations in the vertical bearing loads caused by the overturning moments were large enough to cause reversal of the bearing axial force from compression to tension (Figure 3a).

## Concluding Remarks

Experimental and analytical studies of a seismically isolated building were conducted to understand the behavior of a novel uplift-prevention Friction Pendulum isolator. The shake-table testing on the earthquake simulator at the University at Buffalo utilized a five-story model structure having a slender configuration. The testing program involved a number of simulated ground motions with a variety of frequency content and amplitude.

A comprehensive analytical model was developed to predict the dynamic response of the model structure. The computer program 3D-BASIS-ME was enhanced to include an element representative of the mechanical behavior of the new XY-FP isolator and used for comparison with experimental results.

This investigation led to the following conclusions:

1. The experimental results generated demonstrate the effectiveness of the new XY-FP isolators in uplift prevention.
2. Satisfactory experimental evidence has been provided for the validity of the new XY-FP isolator model incorporated in 3D-BASIS-ME.
3. The response of the isolated structures subjected to severe earthquakes can be accurately predicted by analytical procedures.

## Acknowledgments

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