Paper No. # 901421

Hybrid Shake Table for the Testing of Midlevel Seismic Isolation Systems

Andreas H SCHELLENBERG 1
Pacific Earthquake Engineering Research Institute, University of California, Berkeley
325 Davis Hall, University of California, Berkeley, CA 94720 USA
andreas.schellenberg@gmail.com

Tracy C BECKER 2
Disaster Prevention Research Institute, Kyoto University
Gokasho, Uji, Kyoto 611-0011 Japan
becker.tracy.75c@st.kyoto-u.ac.jp

Stephen A MAHIN 3
Pacific Earthquake Engineering Research Institute, University of California, Berkeley
325 Davis Hall, University of California, Berkeley, CA 94720 USA
mahin@berkeley.edu

ABSTRACT

Many structures exhibit significant rate of loading effects that suggest that they need to be tested at or near real time. In the case of friction-isolated structures, this rate dependency poses a major problem for tests involving quasi-static hybrid simulations where tests are executed slower than real-time. In an effort to examine the behavior of seismically isolated structures with the isolation plane located in the upper stories of the structure rather than at the base, hybrid shake table tests were performed where the substructure was modeled numerically, and the isolation system and superstructure were tested experimentally. An isolation plane that is located in the upper stories provides a means to reduce higher mode effects on the response of the structure. Furthermore, the isolated portion of the structure provides supplemental inertial based energy dissipation on the overall seismic response of the tall building.

For this series of experimental tests, a seismically isolated two-story steel moment resisting frame, resembling the superstructure of the tall building, was placed on a specially designed and constructed unidirectional hybrid shake table. The moment frame test specimen was supported on six triple friction pendulum isolators, designed to minimize accelerations in the upper portions of the building and to increase energy dissipation at the isolation level. The structure was then subjected to a number of excitations where the height and period of the substructure below the isolation plane is varied to examine the effectiveness of the isolation concept for different building configurations, and the ability of the hybrid simulation method to accurately test midlevel seismic isolation concepts is also evaluated.

Keywords: *hybrid testing, shake table, friction pendulum, isolation, midlevel isolation*

1 INTRODUCTION

In many countries, seismic isolation technology is increasingly being used to improve the performance of buildings and bridges and avoid significant structural damage by concentrating large deformations in the isolators and providing supplemental energy dissipation through the isolation system during ground shaking. For various reasons, the isolation plane is no longer always placed at the base of the building as was common practice historically. Over the last decade, midlevel seismic isolation systems, where the isolation plane is placed higher up the building instead of at the base, have been studied [1, 2, 3, 4] and several tall midlevel isolation building projects have been designed and constructed, especially in Japan [5, 6]. Midlevel seismic isolation systems can provide the following benefits versus conventional tall building construction practices:

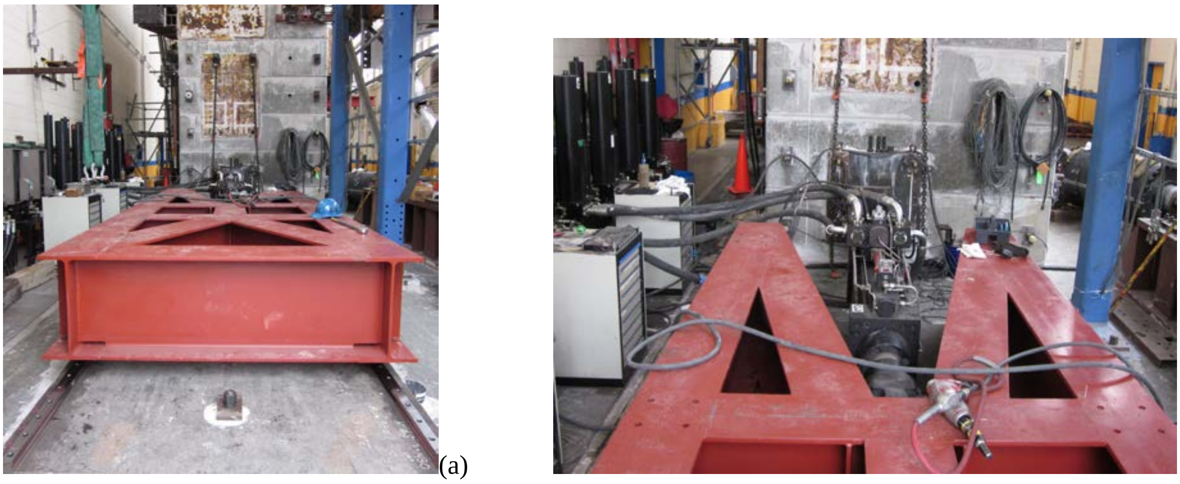
- Provide more architectural flexibility, necessary in multi-use applications where transitions between different structural systems are required.
- Concentrate deformations and energy dissipation in the isolation level, reducing seismic demands on both the super- and substructure and eliminating structural damage.
- Facilitate the addition of new stories on top of existing buildings while minimally increasing seismic demands on the existing building by exploiting the unturned mass-damper effect that is introduced by the isolated superstructure.

However, because the dynamics of midlevel isolated buildings is dependent on the interaction between the sub- and superstructure, multiple large scale configurations become unfeasible by standard experimental testing methods. In order to efficiently test the interaction between an isolated superstructure with a range of substructure configurations, the hybrid shake table testing method was adopted [7]. Friction pendulum bearings were selected for the isolation bearings, which exhibit a strong rate-dependency especially at low velocities; thus, the hybrid control needed to be in real time and a unidirectional hybrid shake table was built for the project. This setup allows for extended study into the behavior of midlevel isolated buildings.

2 EXPERIMENT DESCRIPTION

The hybrid test was composed of an experimentally tested isolated two story moment frame that represented a superstructure and a numerically simulated lumped mass substructure. A unidirectional shake table was constructed for the real time loading. The shake table, shown in Figure 1, consists of a large steel platform isolated on linear guide rails. The friction in the rails was specified as less than 10%. The steel platform is 5.8 m long by 2 m wide. The platform is supported at six points, directly below the locations of the frame columns. The shake table is driven by an MTS actuator with +/- 50 cm of stroke and 667 kN force capacity. The table is controlled using an MTS 493 Real-Time Controller. The digital controller provides closed-loop PID, differential Feedforward, and Delta-P control capabilities.

The basic outline of the hybrid test is shown in Figure 2. Earthquake excitation is input into the base of the numerical substructure, modeled in OpenSees [8]. The absolute displacement at the top of the numerical substructure is the target displacement, which is sent to OpenFresco [9, 10]. OpenFresco serves as the middleware which is used to interface the numerical substructure with the experimental superstructure through the control system. A predictor-corrector algorithm is then used to bridge the difference between the analysis time step size and the smaller control system time step size. The command displacement generated by the predictor-corrector algorithm is sent to the controller which controls the actuator driving the shake table. The resulting displacement of the table and the shear force under the physical specimen – recorded using loads under each of the isolators – are measured. The measured displacement is fed back into the controller and predictor-corrector algorithm while the measured shear force is fed into the numerical OpenSees model for the next analysis time step.



(a) (b)

Figure 1 – Unidirectional shake table

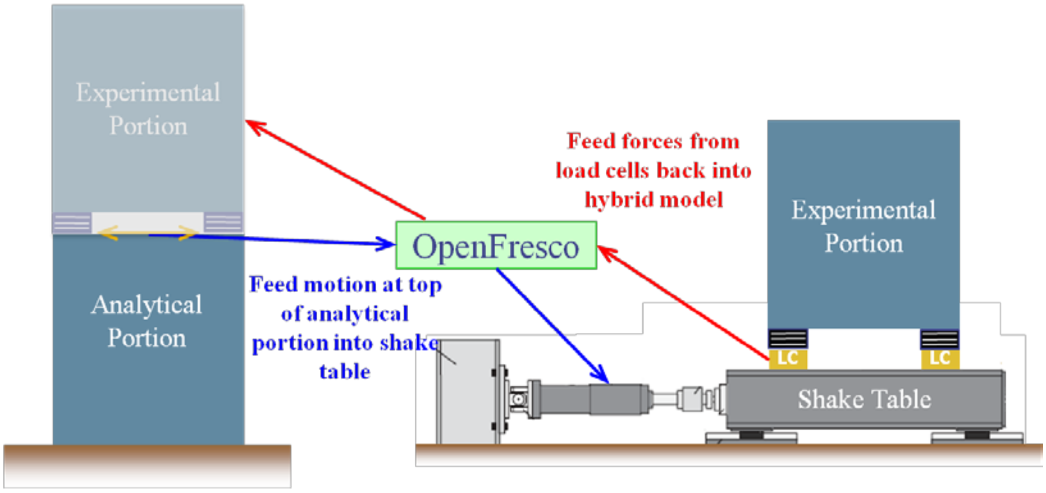


Figure 2 – Data flow in the hybrid shake table test

2.1 Isolated Superstructure and Input Ground Motion

The physical superstructure was a 1/3rd scale steel moment frame isolated on six triple friction pendulum (TFP) bearings, shown in Figure 3. The cross section and properties of the TFP bearings are shown in Figure 4. The ultimate displacement capacity of the model-scale isolators is 178 mm. The equivalent elastic period of the bearings is 1.4 seconds at 100 mm. The ground motions used in the tests were scaled for use in later tests when the input displacement would be applied directly to the isolated frame, without a numerical substructure. The motions were scaled so that in those tests the expected displacement of the bearings was just within the maximum displacement of the bearings under the maximum considered earthquake level, or 2% chance of exceedance in 50 years. In this paper, we discuss the response to the Loma Prieta Gilroy #4 Array under the design level earthquake, or 10% chance of exceedance in 50 years. The fault normal component of the motion was used in the experiments. The acceleration time history was multiplied by 0.70 for this level. In addition, a length scale of 3 was used to match the scale of the physical specimen.

The superstructure frame is two stories with an additional beam level above the isolators. The first story is 1.7 m and the second story is 1.5 m. The frame has two bays in the direction of loading with a span of 2.44 m. The frame was constructed using the NEES Reconfigurable Platform for Earthquake Testing (REPEAT frame) which has HSS beam and column sections that can be connected to joint pieces using clevises. These clevises have holes for coupon pieces that are sized to the desired moment capacity of the section, mimicking plastic hinge behavior. Thus, after the frame yields, the coupons can be replaced and the frame can be used again. The coupons used in these experiments were designed so that the frame would begin to yield at the same time the bearings reached their ultimate displacement capacity, at roughly 30% g. The frame was loaded with additional concrete blocks to reach a total weight of 356 kN so that the pressure on the sliding surfaces in the isolators would be large enough to ensure stable friction behavior.

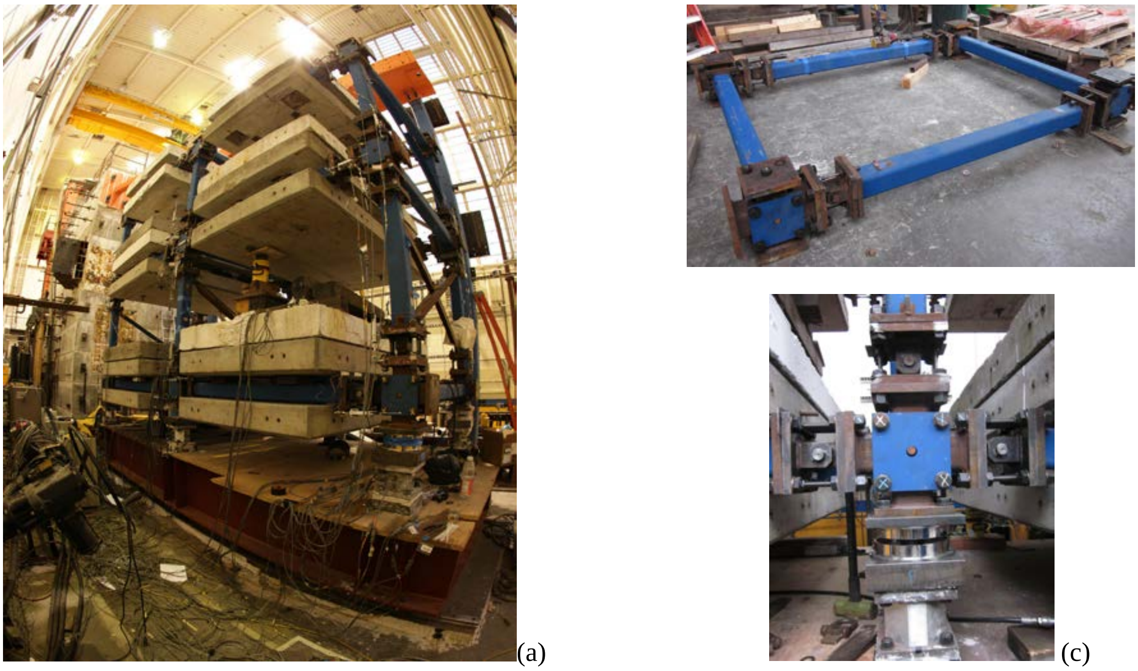
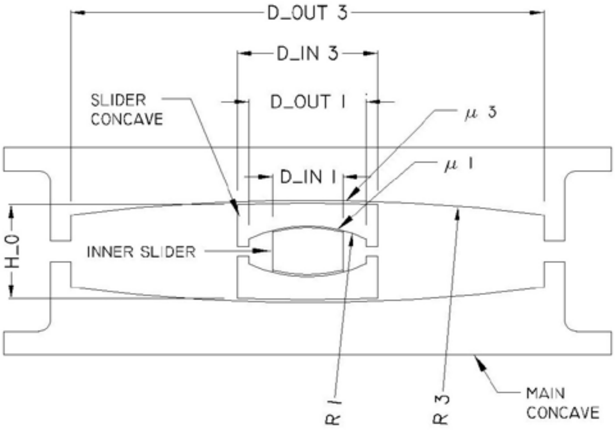

(a) (b) (c)

Figure 3 – (a) Isolated frame superstructure installed on the shake table (b,c) REPEAT frame components



PROPERTY	VALUE
R 1	3.00"
R 3	18.64"
D_IN 1	1.5"
D_IN 3	3.0"
D_OUT 1	2.5"
D_OUT 3	9.0"
H_0	6.0"
μ 1	2%
μ 3	9%

Figure 4 – Triple friction pendulum cross section and properties

2.2 Numerical Substructure

Multiple substructure configurations were used to examine both the ability of the hybrid model to be tested in real time with various properties for the numerical portion, as well as to examine the change in the dynamic interaction of the isolated superstructure with different substructures. As seen in Figure 5, two main substructure configurations were used: a one story and a three story building. Both configurations used simple numerical shear building and lumped-mass modeling assumptions, the properties of which are listed in Table 1. The one story building, or Model A, was assigned a weight equal to roughly the total weight of the superstructure. The period of Model A was changed from 0.13 to 1.01 seconds in the tests. For the three story building, or Model B, each floor had a weight approximately equal to the bottom floors of the superstructure. The period of Model B was changed from 0.25 to 1.02 seconds in the tests. Both models were assigned 3% equivalent viscous damping and were assumed to remain linear elastic.

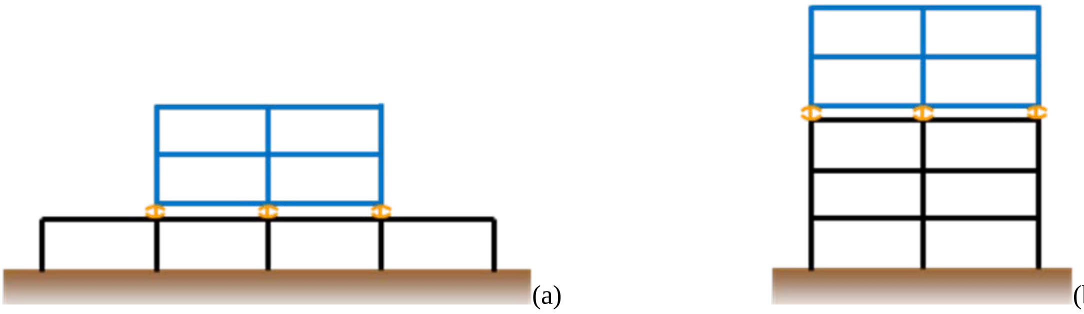


Figure 5 – Hybrid model configurations, blue indicates the physical specimen, black indicates the substructure: (a) Model A (b) Model B

Table 1 – Numerical substructure parameters

	Floor Weight (kN)	*Story Stiffness (kN/m)*	*Period (s)*	*Damping ratio*
1 Story – Model A	445	1.75	1.01	0.03 (Stiff Prop)
	445	7	0.51	0.03 (Stiff Prop)
	445	28	0.25	0.03 (Stiff Prop)
	445	112	0.13	0.03 (Stiff Prop)
3 Story – Model B	142	2.8	1.02 (0.36, 0.25)	0.03 (Rayleigh)
	142	11.2	0.51 (0.18, 0.13)	0.03 (Rayleigh)
	142	44.8	0.25 (0.09, 006)	0.03Rayleigh)

3 RESULTS

3.1 Experimental Control

Before discussing the behavior of the midlevel isolated buildings, it is important to look at the ability of the hybrid simulation transfer system to accurately connect the numerical and physical potions of the test. Figure 6 shows the displacement histories at the top of the numerical substructure, which are the target input displacements into the shake table, the error histories between the target displacements and the measured displacements, and the FFT's of the error signals. Figure 7 shows the tracking indicator histories in units of length squared, which gives a measure of the enclosed area in a synchronization subspace plot where the measured displacement is plotted against the target displacement. An increasing tracking value indicates a lead in the control while a decreasing value indicates a lag. An overall positive value indicates that energy is dissipated due to tracking errors. An overall negative value indicates that energy is added to the system due to tracking errors. Peak substructure responses are listed in Table 2.

In general, the shorter the period of the substructure, the larger the error is. For the 1 s period substructures, the displacement error was less than 2% of the target. Comparatively, for the 0.25 s period substructures, the displacement error reached 10% of the target. This is also reflected in the tracking indicators which show the largest lag for shorter period structures. However, for Model A, the substructure with a period of 0.125 s had better tracking than the one with a period of 0.25 s. One reason may be seen by looking at the peak floor accelerations at the top of the substructure, listed in Table 2. This is also the peak input acceleration value for the physical superstructure. Larger peak input accelerations tended to result in larger tracking errors. This is a result of the tuning of the shake table controller not being as accurate at these higher acceleration amplitudes and frequencies.

While lag was large for the short period substructures, the FFT's of the errors, shown in Figure 6, are broadband without any conspicuous peaks. Thus, the system was able to reproduce displacements for the full range of desired frequencies. Overall, the hybrid control system produced reasonably accurate results.

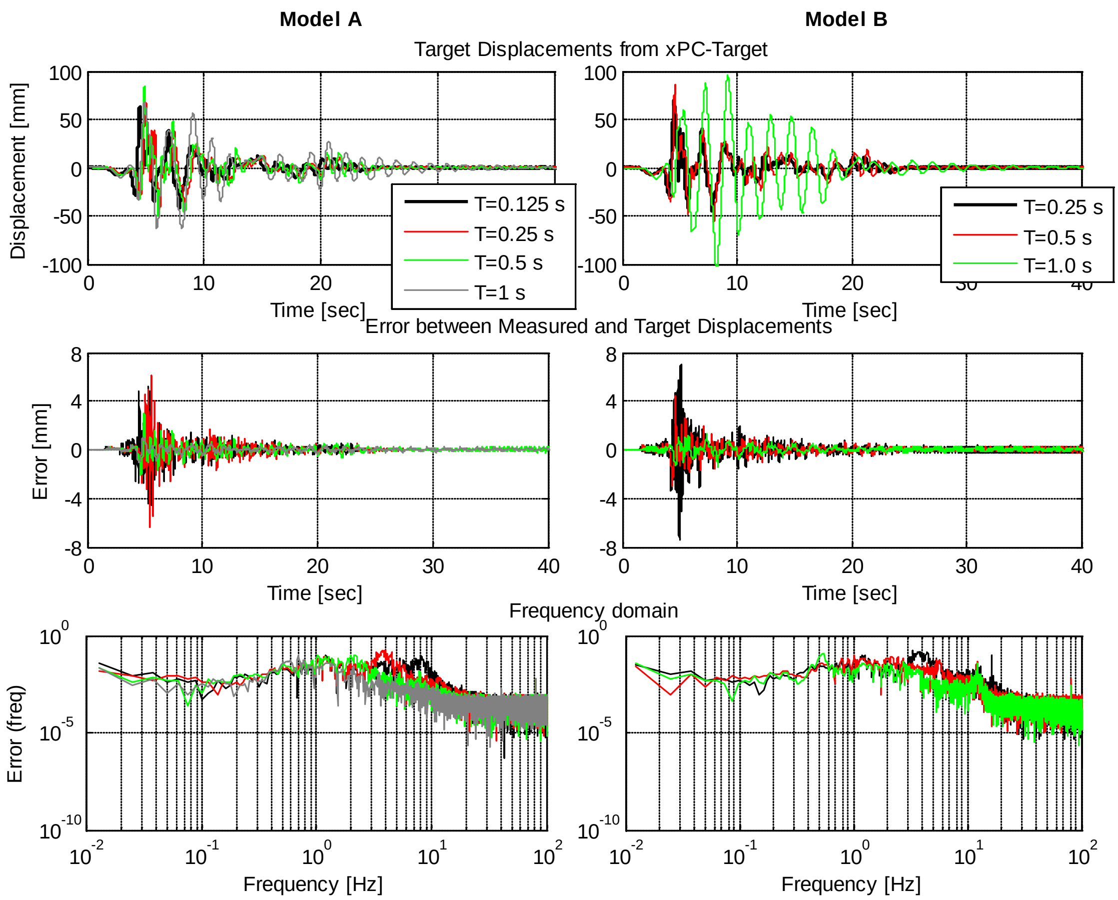


Figure 6 – Numerical substructure top displacement, error between target and measured displacements to the physical superstructure and FFT of the error for the various substructure configurations

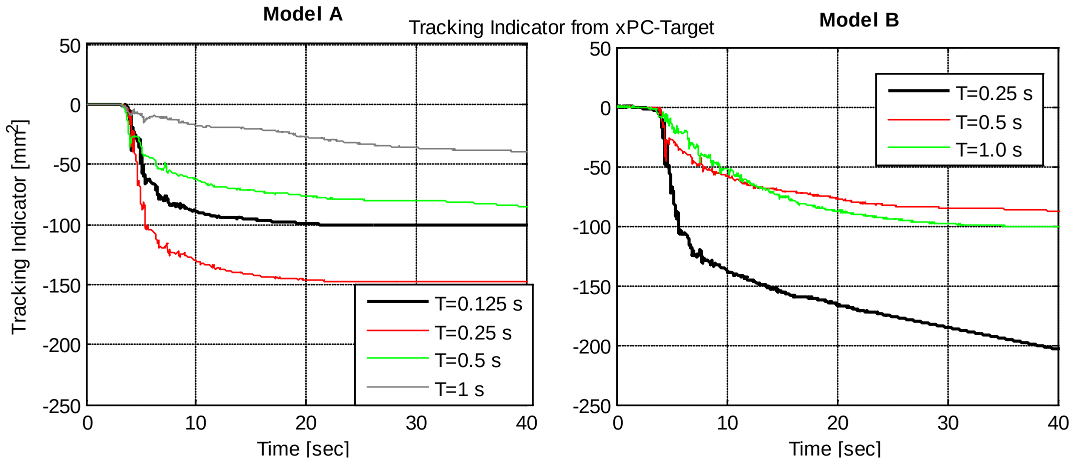


Figure 7 – Control tracking indicators for the various substructure configurations

3.2 Midlevel Isolation

The behavior of the system can be separated into the numerical substructure and physical superstructure. The peak responses of the substructure are given in Table 2. As would be expected, the peak story drift decreased as the period of the structure decreased (stiffness increased). The cumulative story drifts of Model B were on the same order as Model A for the substructures with the same periods. However, the peak floor accelerations were consistently and sometimes significantly larger for Model B, most probably because of the addition of higher modes. Figure 6 shows the displacement time histories for the top of the substructure. Responses are similar for

Model A and B for the shorter period substructures; however, for the 1 s period case, there is a marked difference. For this period, Model B exhibits larger, almost resonant-like behavior compared to Model A.

The peak responses of the experimentally tested isolated superstructure are given in Table 3. As the period of the isolated structure ranged from 1 s to 1.5 s over the level of displacements seen, it might be assumed that having a long period substructure would cause large isolator displacements as the input motion to the superstructure would be filtered to have larger low frequency content. However, Table 3 shows that the peak superstructure responses, including isolator response are the lowest in the case of the 1 s substructure. The level of superstructure response is tied only to input acceleration levels, with larger input accelerations, rather than input displacements, resulting in larger superstructure responses.

The floor response spectra, often used to predict the response of non-structural components, are shown in Figure 8. The spectra confirm that the acceleration responses for all building levels are significantly lower for the substructures with 1 s period. As would be expected, the spectra for the top of the substructure have larger response for higher frequencies for Model B because of the inclusion of higher modes in the model. However, this trend does not transfer to the spectra of the superstructure, which do not change significantly in shape between the two models with the exception of the substructures with 1 s period, whose differences in behavior were discussed above.

Table 2 – Peak Substructure Responses

	Period (s)	*Peak Story Drift (mm)*	*Peak Floor Acceleration (g)*
		-	PGA = 0.58
1 Story – Model A	1.01	70.1	0.16
	0.51	37.5	0.59
	0.25	22.9	1.48
	0.13	14.1	1.10
3 Story – Model B	1.02	31.5 / 29.9 / 28.9	0.41 / 0.42 / 0.23
	0.51	15.5 / 15.0 / 11.9	0.81 / 0.75 / 0.96
	0.25	10.5 / 8.6 / 5.2	0.94 / 1.22 / 1.69

Table 3 – Peak Superstructure Responses

	Period (s)	*Peak Isolator Drift (mm)*	*Peak Isolator Force (% weight of super)*	*Peak Story Drift (mm)*	*Peak Floor Acceleration (g)*
1 Story – Model A	1.01	52	0.18	15 / 5	0.29 / 0.18 / 0.32
	0.51	111	0.22	18 / 8	0.35 / 0.28 / 0.45
	0.25	104	0.23	17 / 9	0.58 / 0.23 / 0.50
	0.13	87	0.24	19 / 8	0.58 / 0.28 / 0.45
3 Story – Model B	1.02	45	0.17	13 / 6	0.25 / 0.18 / 0.30
	0.51	98	0.21	21 / 8	0.46 / 0.29 / 0.50
	0.25	104	0.23	16 / 9	0.81 / 0.24 / 0.56

4 CONCLUSIONS

In order to conduct efficient experimental tests of a midlevel isolated building, a hybrid shake table was constructed. The isolated superstructure was experimentally tested on the shake table while the substructure was numerically modeled using OpenSees; in this way, it was possible to examine the behavior of the midlevel isolation system with multiple substructure configurations. OpenFresco was used as the interface between the numerical and experimental portions of the hybrid test. The response of the isolated superstructure was largest for the shorter period substructures, which input higher acceleration values into the isolated portion. This is in contrast to the response with the long period substructure, which was close to the first period of the isolation system. This indicated that the issue of resonance is not of large concern.

The hybrid testing proved to be a reliable testing method for the midlevel isolation and the system was able to reliably reproduce the full range of input frequencies. However, large control lags occurred with the 0.25 s period substructure, possibly because of the tuning of the shake table. Also, for the long period system, large differences were seen in the behavior of the substructure response when single versus multiple degrees of freedom were used to model the substructure. Both these issues require further investigation.

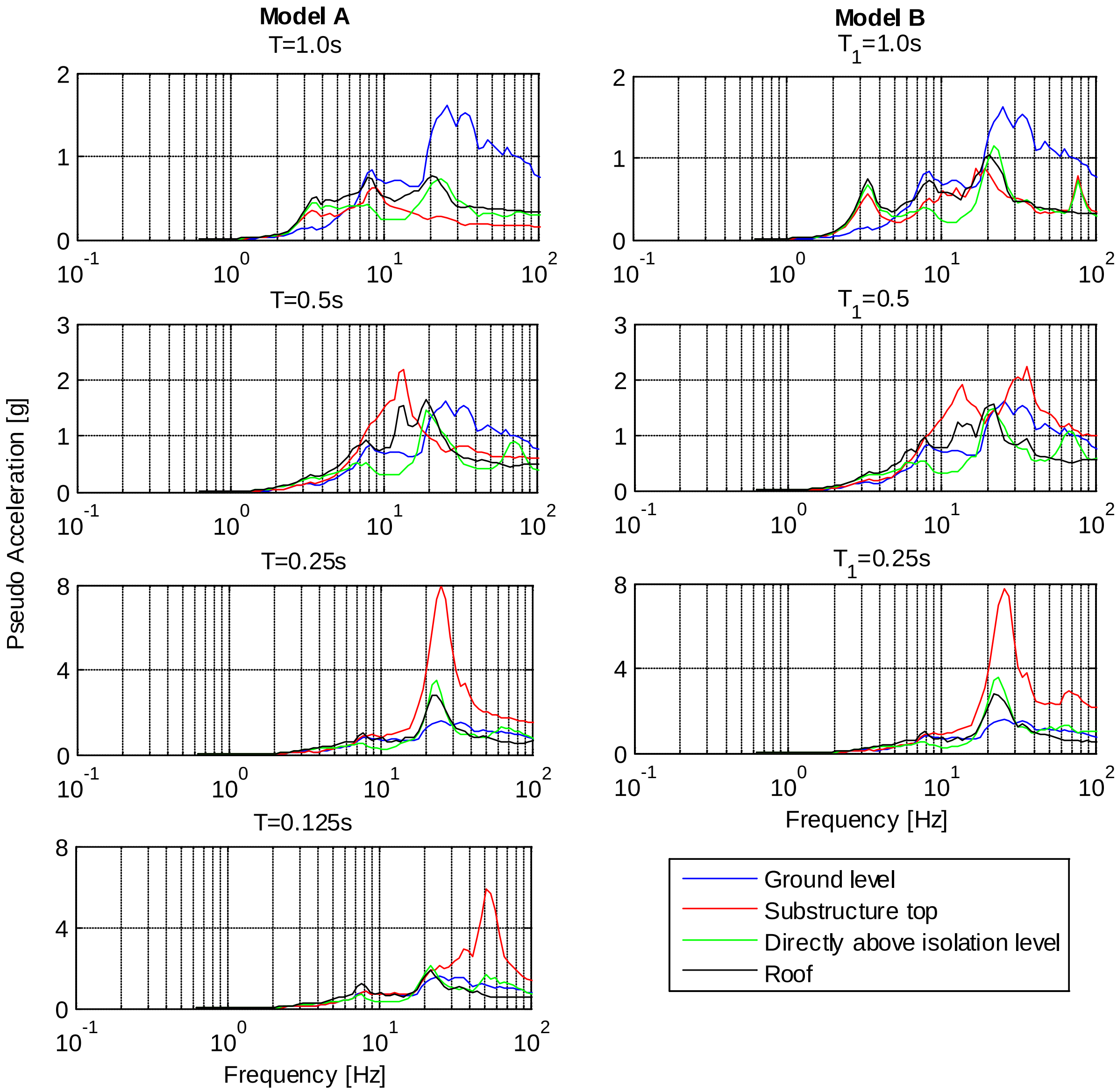


Figure 8 – Input and substructure top floor response spectra for the various substructure configurations

REFERENCES

[1] Ziyaeifar, M. & Noguchi, H. : Partial mass isolation in tall buildings, *Earthquake Engineering and Structural Dynamics*, Vol. 27 No. 1, 49-65, 1998

[2] Ogura K., Takayama M., Tsujita O., Kimura Y., & Wada A. : Seismic response of mid-story isolated buildings, *Journal of Structural and Construction Engineering, Architectural Institute of Japan* Vol. 516, 99–104, 1999

[3] Villaverde R., & Mosqueda G. : Aseismic roof isolation system: Analytical and shake table studies. *Earthquake Engineering and Structural Dynamics*, Vol. 28 No.3, 217–234, 1999

[4] Wang S.J. et al. : Simplified analysis of mid-story seismically isolated buildings, *Earthquake Engineering and Structural Dynamics*, Vol.40 No.2, 119–133, 2010

[5] Murakami, K., Kitamura, H., Ozaki H., & Yamanashi T. : Design of a building with seismic isolation system at the mid-story, *Journal of Technology and Design, Architectural Institute of Japan* No.7, 51-56, 1999

[6] Sueoka, T.,Torii S., & Tsuneki Y. : The application of response control design using middle-story isolation system to high-rise building, *Proceedings of 13WCEE*, Vancouver, B.C., Canada, 2004

[7] Igarashi, A., Iemura, H., & Suwa, T. : Development of substructured shaking table test method, *Proceedings of 12WCEE*, Auckland, New Zealand, 2000

[8] OpenSees, 2012, Open System for Earthquake Engineering Simulation, from http://opensees.berkeley.edu

[9] Schellenberg, A. H., Mahin, S. A., & Fenves, G.L. : *Advanced Implementation of Hybrid Simulation*. Report No. 2009/104, Pacific Earthquake Engineering Research Center, University of California, Berkeley, California, 2009

[10] OpenFresco, 2012, Open Framework for Experimental Setup and Control, from http://openfresco.berkeley.edu