Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

DEVELOPMENT OF A LARGE SCALE HYBRID SHAKE TABLE AND APPLICATION TO TESTING A FRICTION SLIDER ISOLATED SYSTEM

A. Schellenberg[1], T. C. Becker[2] and S. A. Mahin[3]

ABSTRACT

A unidirectional hybrid control shake table was constructed at the NEES lab at the University of California Berkeley. The 2 m by 6 m table is controlled using an MTS 493 Real-Time Controller. The control system provides PID closed loop control. The ability to have real-time hybrid shake table control is especially important for systems that have strong rate dependencies, such as friction sliding systems. A series of tests was carried out using a 1/3rd scale friction pendulum isolated specimen to examine the viability of hybrid simulation techniques to perform experimental simulations of tall buildings with midlevel seismic isolation. The isolation system and superstructure were physically tested on the table while the portion of the building below the isolation plane was numerically modeled. Numerical modeling was done using OpenSees, and OpenFresco was used to interface between the numerical model and the control system. The isolated superstructure consisted of a one bay by two bay, two story steel moment frame on six triple friction pendulum bearings. These bearings have significant nonlinear behavior. The superstructure was expected to remain elastic; however, a small amount of yielding occurred. Various models were used to represent the portion of the building below the isolation plane, ranging from one to three degree of freedom models with periods from 0.125 to 1.0 seconds. Increasing the numbers of degrees of freedom increased the control difficulty as higher modes were excited in the numerical model. However, the results illustrate that hybrid shaking table tests are indeed feasible and produce reasonably accurate results.

[1]Research Engineer, Dept. of Civil and Env. Eng., Univ. of California, Berkeley, CA, 94720
[2]Assistant Professor, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, Canada
[3]Byron and Elivra Nishkian Professor, Dept. of Civil and Env. Eng., Univ. of Calif., Berkeley, CA, 94720

Schellenberg, A., Becker, T.C., Mahin, S.A. Development of a large scale hybrid shake table and application to testing a friction slider isolated system. *Proceedings of the 10th National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

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A unidirectional hybrid control shake table was constructed at the NEES lab at the University of California Berkeley. The 2 m by 6 m table is controlled using an MTS 493 Real-Time Controller. The control system provides PID closed loop control. The ability to have real-time hybrid shake table control is especially important for systems that have strong rate dependencies, such as friction sliding systems. A series of tests was carried out using a 1/3rd scale friction pendulum isolated specimen to examine the viability of hybrid simulation techniques to perform experimental simulations of tall buildings with midlevel seismic isolation. The isolation system and superstructure were physically tested on the table while the portion of the building below the isolation plane was numerically modeled. Numerical modeling was done using OpenSees, and OpenFresco was used to interface between the numerical model and the control system. The isolated superstructure consisted of a one bay by two bay, two story steel moment frame on six triple friction pendulum bearings. These bearings have significant nonlinear behavior. The superstructure was expected to remain elastic; however, a small amount of yielding occurred. Various models were used to represent the portion of the building below the isolation plane, ranging from one to three degree of freedom models with periods from 0.125 to 1.0 seconds. Increasing the numbers of degrees of freedom increased the control difficulty as higher modes were excited in the numerical model. However, the results illustrate that hybrid shaking table tests are indeed feasible and produce reasonably accurate results.

Introduction

In many countries seismic isolation technology is increasingly being used to improve the performance of buildings and bridges and to 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

[1]Research Engineer, Dept. of Civil and Env. Eng., Univ. of California, Berkeley, CA, 94720
[2]Assistant Professor, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, Canada
[3]Byron and Elivra Nishkian Professor, Dept. of Civil and Env. Eng., Univ. of Calif., Berkeley, CA, 94720

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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 un-tuned 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 methods. In order to efficiently test the interaction between an isolated superstructure with a range of substructure configurations, the hybrid testing method was adopted. 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.

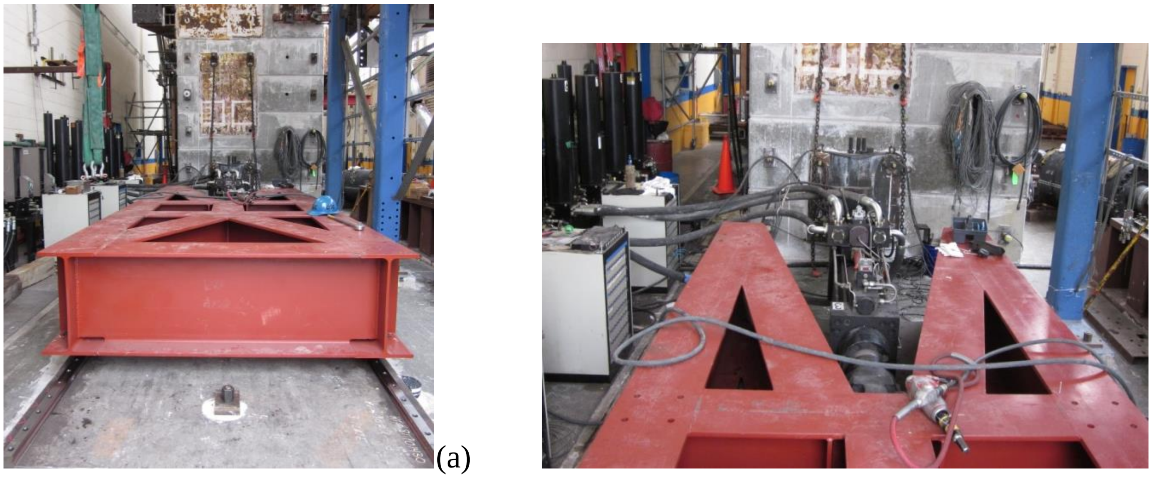
Experiment Description

The hybrid test was composed of an experimentally tested isolated two story moment frame that represented a superstructure and a numerically simulated lumped-mass shear-building 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 low-friction 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 1000 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 [7]. The absolute displacement at the top of the numerical substructure is the target displacement, which is sent to OpenFresco [8]. 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 (5/1024 sec) and the smaller control system time step size (1/1024 sec). 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.

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 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.



(a) (b)

Figure 1. Unidirectional shake table.

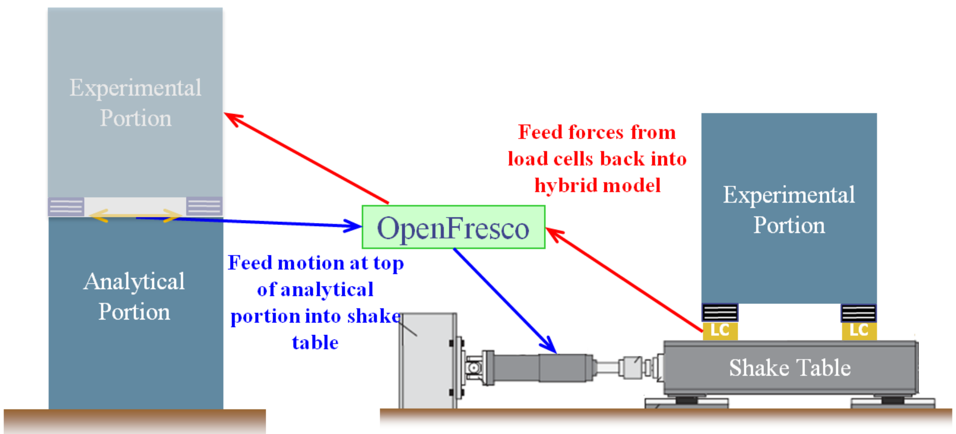
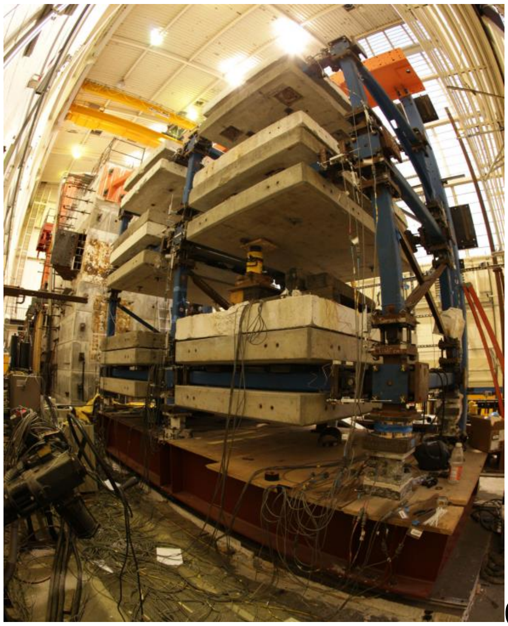


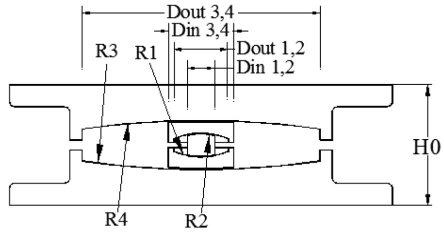
Figure 2. Data flow in the hybrid shake table test.

The ground motions 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 (MCE) level, or 2% probability of exceedance in 50 years. In this paper we discuss the response to the Loma Prieta Gilroy #4 Array under the design basis earthquake (DBE) level, or 10% probability 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 sqrt(3) was used to match the scale of the physical specimen.

The superstructure frame is two stories with an additional diaphragm 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). The frame was designed 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. The fixed base periods of the superstructure are roughly 0.43 sec and 0.14 sec, found through matching a numerical model to the experimental data.



(a)

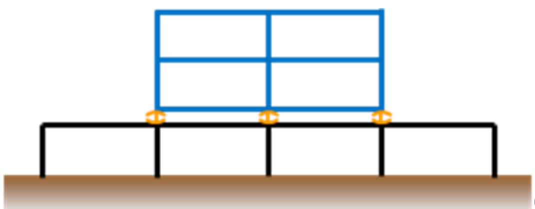


(b)

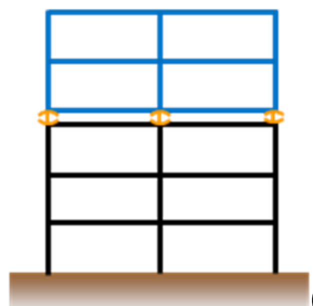
Property	Value
R1,2	3.0 in
R3,4	19.64 in
Din 1,2	1.5 in
Din 3,4	3.0 in
Dout 1,2	2.5 in
Dout 3,4	9.0 in
H0	6 in
Mu 1,2	3%
Mu 3,4	13%

(c)

Figure 3. (a) Isolated frame superstructure installed on the shake table (b,c) triple friction pendulum bearing and properties



(a)



(b)

Figure 4. 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	1750	1.01	0.03
	445	7000	0.51	0.03
	445	28000	0.25	0.03
	445	112000	0.13	0.03
3 Story – Model B	142	2800	1.02 (0.36, 0.25)	0.03 (Rayleigh)
	142	11200	0.51 (0.18, 0.13)	0.03 (Rayleigh)
	142	44800	0.25 (0.09, 006)	0.03 (Rayleigh)

Numerical Substructure

Multiple substructure configurations were used to examine the ability of the hybrid model to be tested in real time with various properties for the numerical portion. Two main substructure configurations were used: a one story and a three story building, shown in Figure 4. Both configurations used simple numerical shear-building and lumped-mass modeling assumptions, the properties of which are listed in Table 1. The one story substructure, or Model A, was assigned a weight roughly equal to the total weight of the superstructure. The period of the Model A substructure was changed from 0.125 to 1.01 seconds in the tests. For the three story substructure, or Model B, each floor had a weight approximately equal to the bottom floors of the superstructure. The period of the Model B substructure 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.

Results

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 5 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 6 shows the tracking indicator histories, which give 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 and vice versa an overall negative value indicates that energy is added to the system due to tracking errors. Peak substructure responses are listed in Table 2 while peak superstructure results are listed in Table 3.

In general, the shorter the period of the substructure, the larger the error between the target and measured displacements. For the 1.0 sec period substructures, the displacement error was less than 2% of the target. Comparatively, for the 0.25 sec 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 0.125 sec had better tracking than for the 0.25 sec motion. The peak floor accelerations at the top of the substructure are 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 because for a given set of linear, non-adaptive control system tuning parameters shake table performance gets worse the larger the requested peak accelerations and the larger the requested frequency content is. Additionally, for the larger peak input accelerations the isolation system exhibited larger isolator deformations (more nonlinearity), which also makes tracking more difficult using a linear control algorithm. While lag was large for the short period substructures, the FFT's of the errors, shown in Figure 5 are broadband with only very minor peaks at the substructure frequencies. Thus, the system was able to reproduce displacements for the full range of desired frequencies.

The Fourier transforms of the acceleration histories of the 0.25 sec substructure case is shown in Figure 7. When comparing Model A and Model B, Model B exhibits conspicuous peaks at high frequencies (14 Hz and 17 Hz) that are not present in Model A. These high frequency peaks correspond to the 5th and 6th modes of Model B, shown in Figure 8. In a full scale test, or real world application, these modes would not be expected to be this pronounced. However, in the hybrid test, the modes are excited due to the high frequency nature of the experimental errors, especially the oil column frequency errors of the transfer system. Peak floor accelerations at the substructure roof were consistently and sometimes significantly larger for Model B, because of the addition of higher modes.

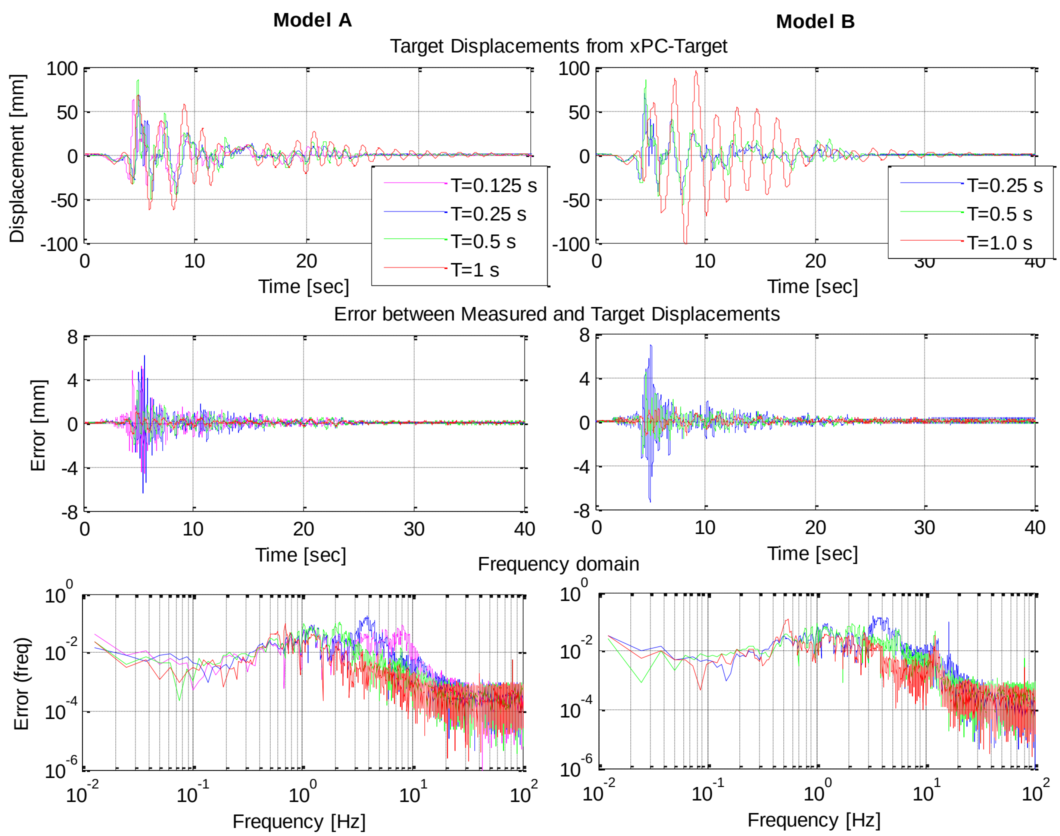


Figure 5. Numerical substructure top displacement, error between target and measured displacements to the physical superstructure and FFT of the error for the various substructure configurations.

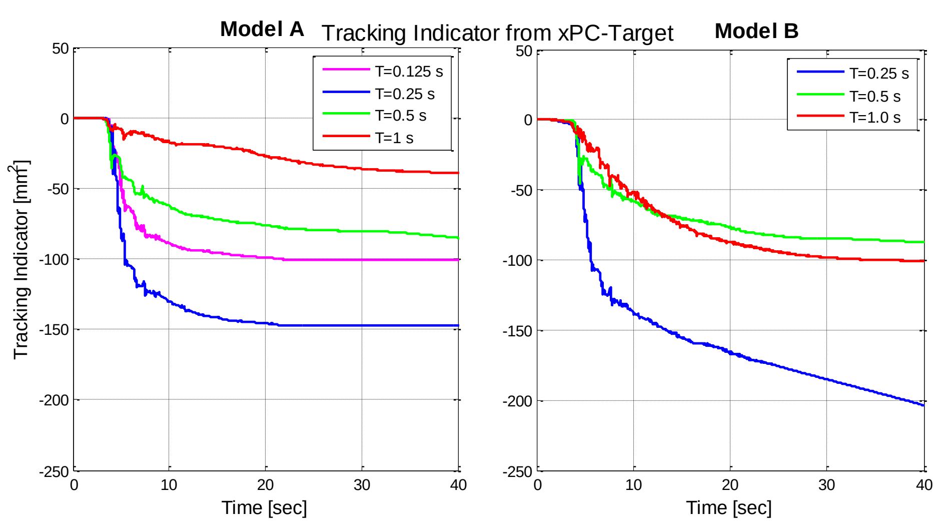


Figure 6. Control tracking indicators for the various substructure configurations.

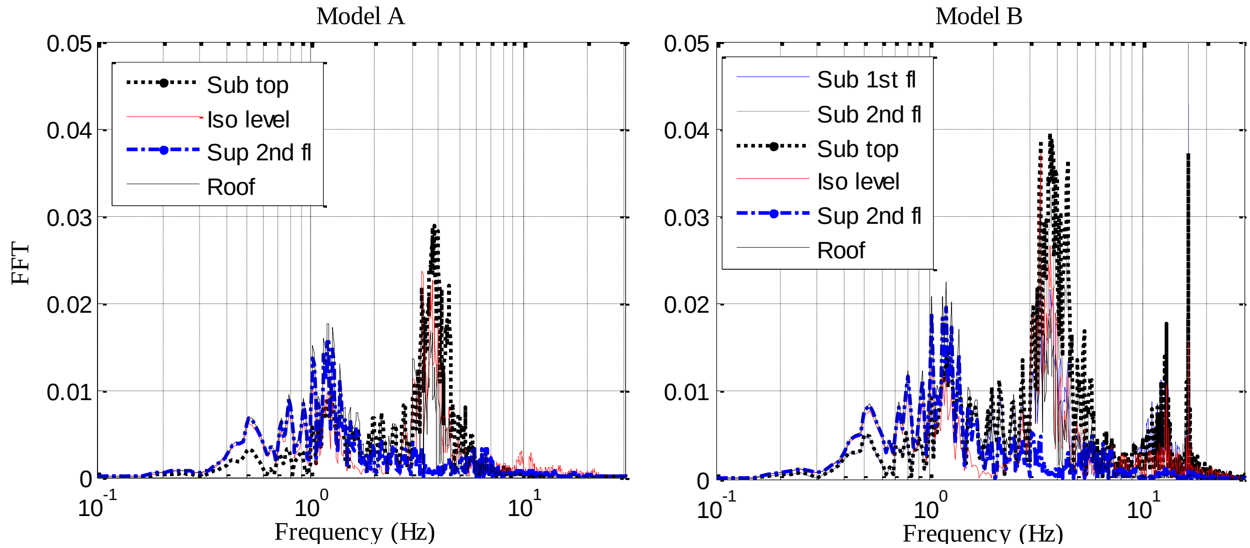


Figure 7. FFT's of the acceleration time histories for the 0.25 sec substructure case.

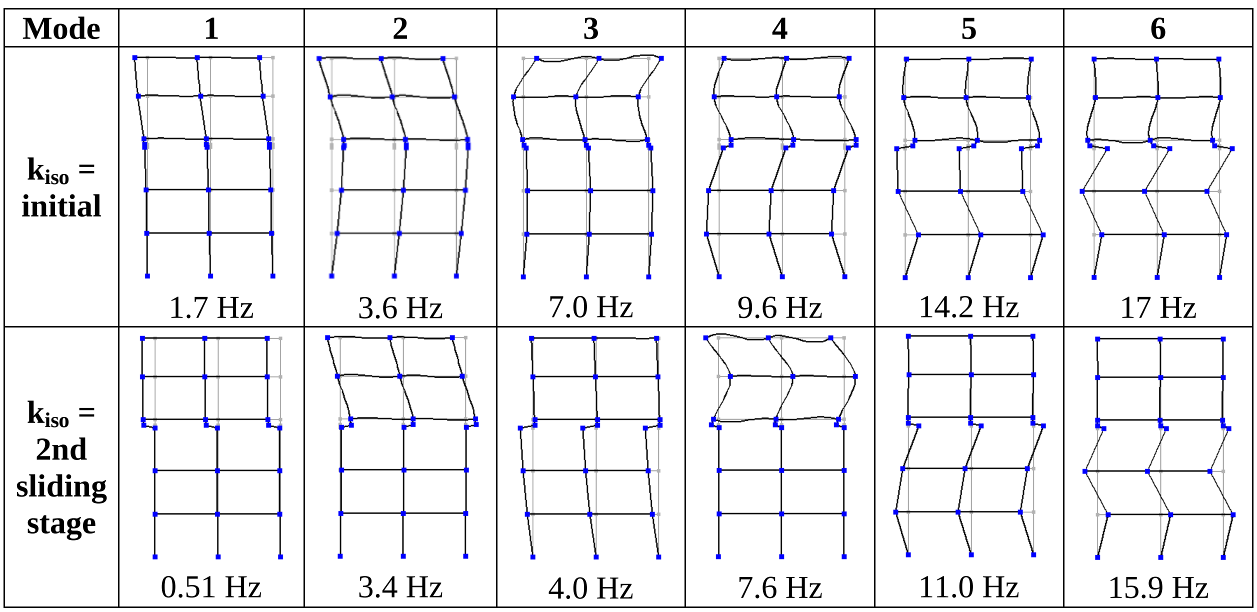


Figure 8. Mode shapes and frequencies for Model B.

Midlevel Isolation

The behavior of the building 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. Figure 5 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 1.0 sec 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 and the isolator hysteresis loops are depicted in Figure 9. As the isolation period ranged from 1.0 sec to 1.5 sec 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 1.0 sec substructure. The floor response spectra are shown in Figure 10. The spectra at the top of the substructure shows the frequency characteristics of the motion input into the isolated superstructure. Larger isolation response would be expected when there was larger frequency content at lower frequencies, closer to the isolation level frequencies. However, while the frequency content is shifted towards lower frequencies when the substructure period is increased, the level of the content is simultaneously decreased, so that there is no or very little increase in acceleration demand at low frequencies. Thus, the level of superstructure response is tied only to the peak acceleration levels coming from the substructure, with larger accelerations resulting in larger superstructure responses.

The floor response spectra, often used for predicting nonstructural component response, confirm that the acceleration responses for all building levels are significantly lower for the substructures with 1.0 sec period. 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 1.0 sec period, whose differences in behavior were discussed previously.

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

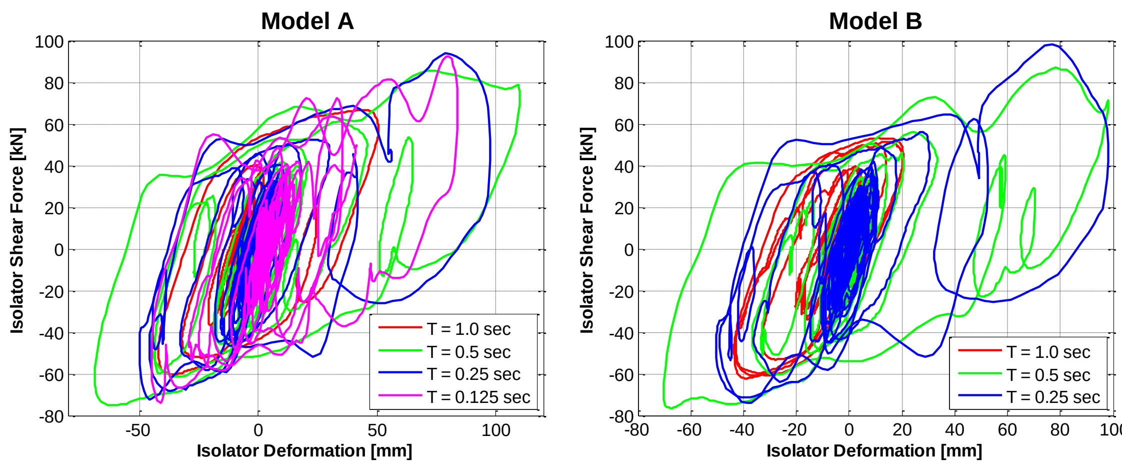


Figure 9. Isolator hysteresis loops for the various substructure configurations.

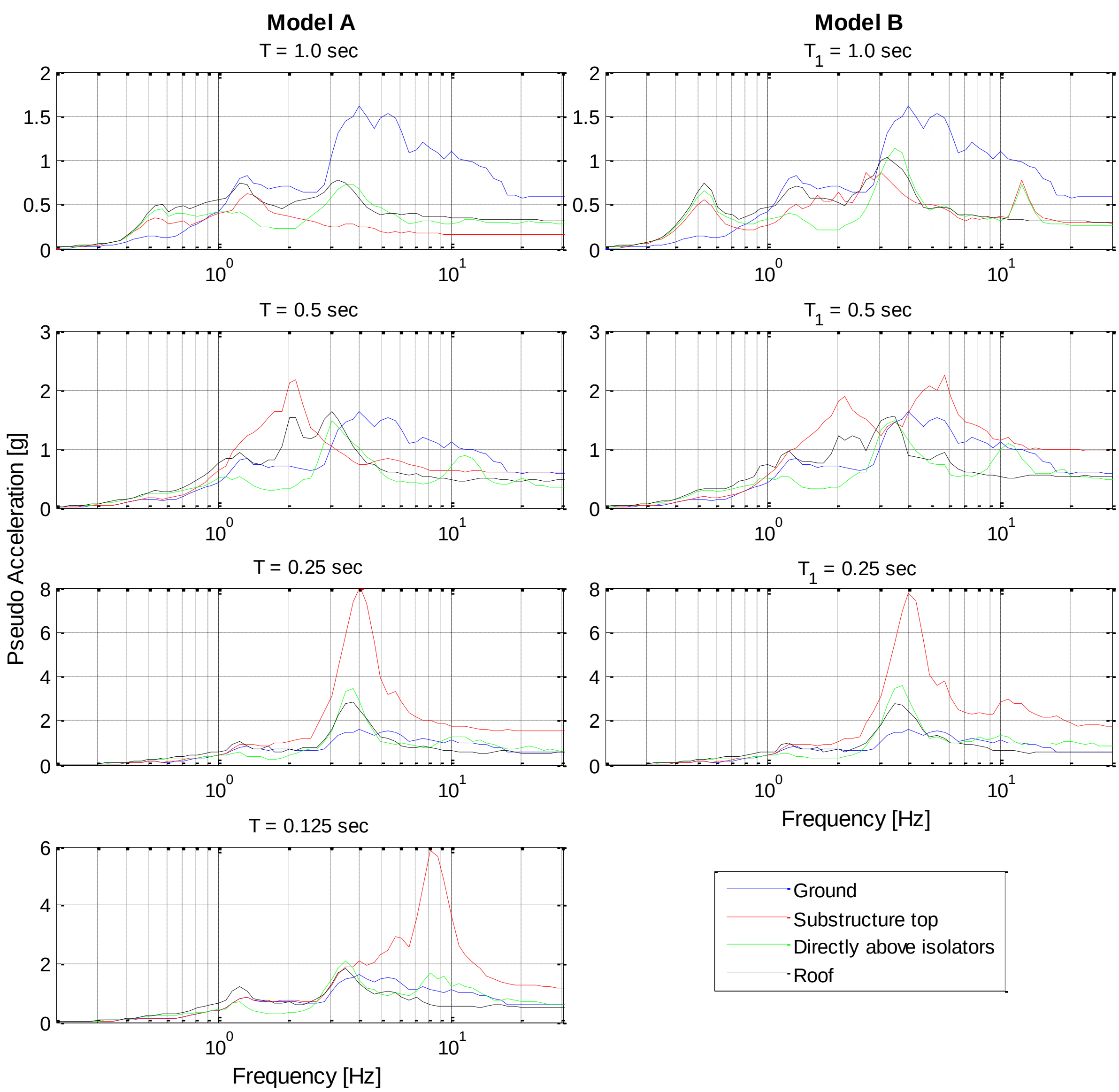


Figure 10. Input and substructure top floor response spectra for the various substructure configurations.

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 indicates 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. 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.

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