16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2117

Registration Code: S-O1462973114

PERFORMANCE VALIDATION OF INTER-STORY ISOLATION THROUGH SHAKE TABLE REAL-TIME HYBRID SIMULATION

R. Zhang[(1)], B.M. Phillips[(2)], S. Taniguchi[(3)], M. Ikenaga[(4)], K. Ikago[(5)]

[(1)] Ph.D. candidate, Department of Civil and Environmental Engineering, University of Maryland, College Park, United States, zhang15@umd.edu

[(2)] Assistant Professor, Department of Civil and Environmental Engineering, University of Maryland, College Park, United States, bphilli@umd.edu

[(3)] M.S. Student, Department of Architecture and Building Science, Tohoku University, Sendai, Japan, kamikanagawa671@gmail.com

[(4)] Associate Professor, Department of Architecture, Faculty of Environmental and Urban Engineering, Kansai University, Osaka, Japan, mikenaga@kansai-u.ac.jp

[(5)] Professor, Department of Architecture and Building Science, Tohoku University, Sendai, Japan, ikago@archi.tohoku.ac.jp

Abstract

While traditional base isolation remains one of the most widely employed systems for mitigating seismic response, inter-story isolation has recently gained popularity, especially in densely populated areas. In inter-story isolation, the isolation system is incorporated between stories instead of the base of the structure. Installing inter-story isolation is simple, inexpensive, and disruption-free in retrofit applications. Benefits include nominally independent structural systems where the accelerations of the added floors are greatly reduced when compared to a conventional structural system. Furthermore, in retrofit applications, the base shear demand on the total structure is not significantly increased. Practical applications of inter-story isolation have appeared in the US and Japan and likewise new design validation techniques are needed to parallel growing interest. Real-time hybrid simulation (RTHS) offers an alternative to investigate the seismic behaviors of high-rise buildings with inter-story isolation. Shake tables are standard equipment in many laboratories, ranging from simple uni-axial tables to six-degree-of-freedom tables. These tables are capable of providing the interface boundary conditions necessary in this application of substructure RTHS. The substructure below the isolation layer can be simulated numerically while the superstructure above the isolation layer can be tested experimentally. This provides a high-fidelity representation of the nonlinearities in the isolation layer, including any supplemental damping devices. However, implementation of RTHS using shake tables is challenging. Shake tables are nonlinear devices exhibiting strong control-structure interaction, making modeling and control a challenging task. Any delay or lag in the realization of the desired table trajectory and measurement of the base shear can introduce inaccuracies and instabilities into the loop. This research investigates the seismic performance of a 14-story high-rise building with inter-story isolation through shake table RTHS. Challenges associated with shake table RTHS are addressed throughout this practical application. To contrast the challenges, the favorable behavior of base-isolated specimens in RTHS from a stability perspective is illustrated. A model-based shake table control approach is successfully implemented on the shake table, exhibiting good offline and online acceleration tracking performance. The methods proposed show that RTHS is an accurate and reliable means to investigate high-rise buildings with inter-story isolation, including new configurations and supplemental control approaches.

Keywords: inter-story isolation; real-time hybrid simulation; shake table control

1. Introduction

While traditional base isolation remains one of the most widely employed systems for mitigating seismic response, inter-story isolation has recently gained popularity, especially in densely populated areas. In inter-story isolation, the isolation system is incorporated between stories instead of the base of the structure. Installing base isolation is straightforward for new buildings, but complicated and costly for retrofit applications, requiring excavation and temporary supports. Installing an isolation system at the roof level is comparatively simple, inexpensive, and disruption free. By using inter-story isolation, accelerations of the added floors are reduced, allowing additional floors to be constructed on an existing structure without increasing the base shear demand.

Moreover, because inter-story isolation nominally separates the building system into two independent structural parts, the upper and lower structures can be designed with different form and function. Some practical applications of inter-story isolation appeared in high-rise buildings in Japan, including the Iidabashi First Building (IFB) [1] and the Shidome Sumitomo Building (SSB) [2, 3]. In both buildings, the upper and lower floors are designed for different purposes and with different structural forms. Inter-story isolation has a large potential to improve the design flexibility in high-rise buildings, especially for multi-purpose buildings, to achieve unique architectural features, and in retrofit applications.

New experimental performance validation techniques are needed to parallel growing interest in inter-story isolation. Real-time hybrid simulation (RTHS) is increasingly recognized as a powerful experiment technique to evaluate the performance of structural components subjected to seismic excitations. RTHS provides an attractive alternative to traditional shake table testing for earthquake engineering studies [4] by combining experimental testing and numerical simulation in an efficient and cost-effective framework.

This study investigates the seismic performance of a 14-story high-rise building with inter-story isolation through shake table RTHS. The proposed framework is verified for a large-scale single-degree-of-freedom (SDOF) base-isolated specimen representing the upper stories including isolation layer and with numerically simulated lower stories. For RTHS, a model-based control strategy consisting of both feedforward and feedback links [5] is proposed to provide the required real-time acceleration control, exhibiting good offline and online acceleration tracking performance. Results compare well with numerical simulations, demonstrating that RTHS is an accurate and reliable means to investigate high-rise buildings with inter-story isolations, including new configurations and supplemental control approaches.

2. Structural Models

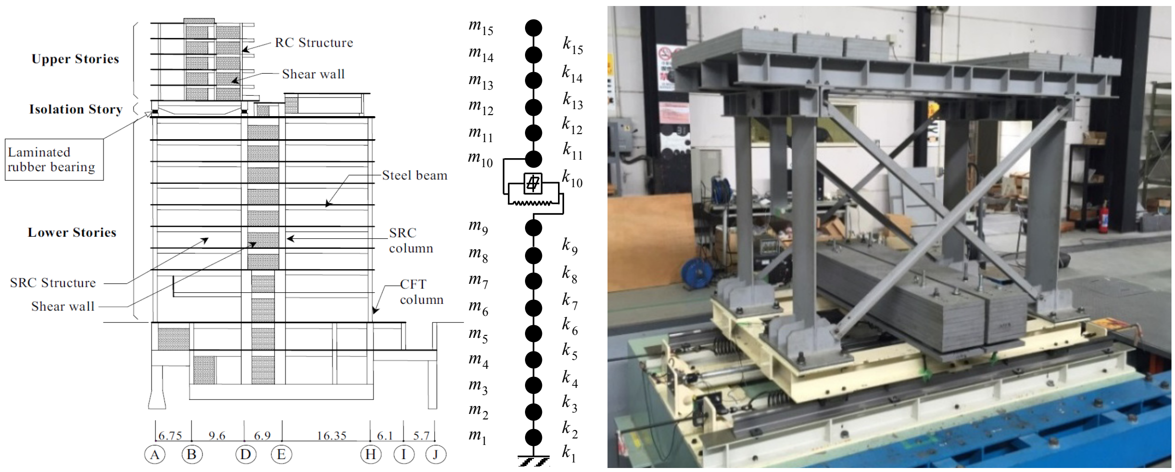
This section illustrates the structural models used in this study, including the target total structure, prototype structure, experimental substructure, and the numerical substructure.

2.1 Target structure

The target structure investigated in this study is the Iidabashi First Building (IFB) [1] located in Tokyo, taken as a realistic representation of high-rise buildings with inter-story isolation. The IFB is a 14-story high-rise building with an inter-story seismic isolation on the 9th floor. Fig. 1(a) shows the structural system and its simplified shear building model. In the IFB, offices are located on the 2nd to 9th floor with large column-free spaces up to about 5,000 m^2, while apartments are located on the 10th to 14th floor. A roof garden is located on the 10th floor, enabled by the change in floor plan. The lower structure is a combination of shear walls and moment resisting frames made from steel reinforced concrete while the upper structure is a shear wall system of reinforced concrete. On the isolation level, both seismic isolators and dampers are installed.

2.2 Experimental substructure

Due to the isolation layer on the 9th floor of the IFB, the upper stories will nominally respond in their first mode. By replacing the upper stories with a SDOF model, a simple physical specimen can represent their dynamics, instead placing emphasis on the isolation layer behavior. In this study, the upper stories and isolation layer are represented by a SDOF base-isolated specimen. Fig. 1(b) shows the specimen with a length of 2.5 m and a height of 2 m, located at Tohoku University. With the braces, the frame behaves as a rigid body. The total mass of the specimen is 5 metric tons. The specimen is mounted on two linear guide rails with very low friction coupled with four steel coil springs at the base. The natural frequency with braces locked is 0.25 Hz, which is similar to the natural frequency of 0.3 Hz for the upper stories of IFB with isolation. The friction force in the isolation system was identified through free vibration tests as 0.062 kN, estimated to provide an equivalent linear damping ratio of 2.4%. To achieve a damping ratio comparable with the IFB isolation system (approximately 15%), a long-stroke magnetorheological (MR) damper in passive-mode was installed in the isolation layer of the specimen.



(a) (b)

Fig. 1 – (a) Structural system of the IFB; (b) Single-story specimen mounted on isolator

2.3 Prototype structure and numerical substructure

A 10-DOF prototype structure is created by scaling the target structure down to be compatible with the experimental substructure, achieving similar natural frequencies and mode shapes as the target structure, and assuming SDOF behavior above the isolation layer. The natural frequencies of the prototype structure are 0.24 Hz, 0.83 Hz, 2.32 Hz, 3.88 Hz, 5.49 Hz, which compare well to the target structure of 0.29 Hz, 1.04 Hz, 2.93 Hz, 4.89 Hz, and 6.89 Hz. Fig. 2 shows the first three mode shapes of the target structure and the prototype structure. The 10^{th} through 15^{th} floor displacement of the prototype structure are identical because of the SDOF assumption. The damping ratios of the prototype structure are selected as 2.23%, 2.80%, 7.74%, 12.9%, and 18.1% in the first five modes, which does not include the contribution from the supplemental damping in the isolation layer.

2.4 Supplemental damping

The target structure contains supplemental dampers in the isolation layer, which are not yet considered in the above models. To replicate the supplemental dampers, a physical MR damper is added to the isolation layer of the test specimen. Based on sine wave tests of the MR damper, the MR damper combined with the inherent friction damping produces approximately 15% damping in the first mode of the specimen for the passive-on state (30V). A phenomenological model, based on a Bouc-Wen hysteretic model, is used to model the MR damper behavior for simulations [6]. The parameters of the model are fit to sine wave tests of varying amplitude and frequency with a 30V in the damper coils.

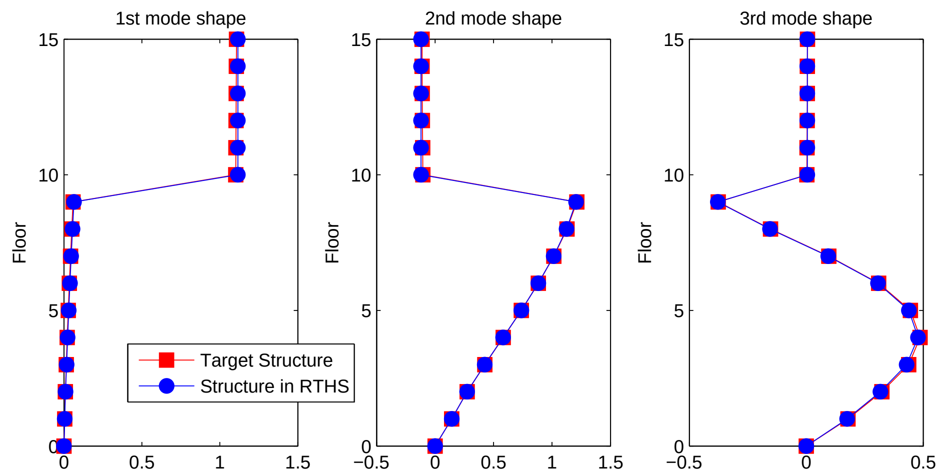


Fig. 2 – First three mode shapes of the target structure and prototype structure (for RTHS)

3. Substructure Shake Table RTHS

To illustrate the framework for shake table RTHS applied to high-rise buildings with inter-story isolation, a 15-DOF structure is considered as shown in Fig. 3(a). Parameters m_i, c_i, and k_i are the mass, damping, and stiffness of the *i*-th story, x_i is displacement relative to the ground of the *i*-th story, $\ddot{x}_g$ is the ground acceleration, and dots represent differentiation with respect to time. For substructure RTHS, the structure is partitioned into numerical and experimental substructures as shown Fig. 3(b) and combined through RTHS as shown in Fig. 3(c). The numerical substructure is selected as the lower 9 stories (below inter-story isolation), while the upper six stories including the isolation layer are tested experimentally. Structural parameters as well as DOF associated with the experimental substructure are indicated by the superscript "E". Structural parameters as well as DOF associated with the numerical substructure are indicated by the superscript "N". The DOF at the interface between components are indicated by the superscript "I". Numerical integration is performed solely on the numerical substructure. This approach is consistent with the dynamic substructuring approach of Shing [7].

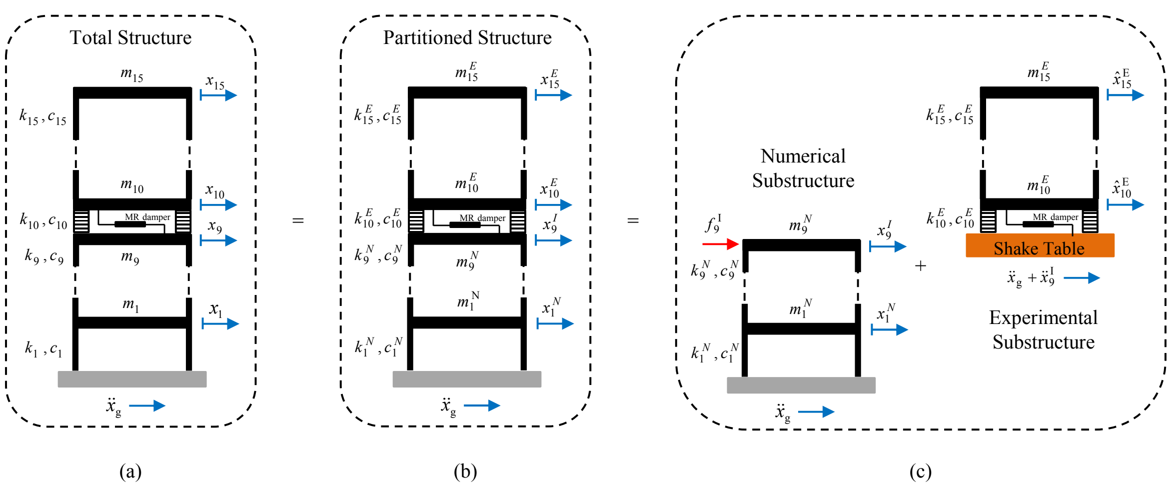


Fig. 3 – RTHS configuration using a shake table for IFB model with inter-story isolations

With this choice of substructuring, the numerical substructure is excited by ground acceleration and the numerical and interface DOF values are determined through numerical integration. The absolute acceleration of the interface DOF is taken as the desired acceleration for the shake table. This acceleration is not known prior to testing, requiring a special class of shake table control strategies that can track accelerations determined online. The base shear of the experimental substructure is returned to the numerical substructure as the contribution from upper stories. This loop of action and reaction is carried out in real time until the entire time history response has been evaluated.

To capture the inertial effects of the experimental substructure, the shake table must be able to track the desired accelerations accurately. Without compensation, the dynamics of the shake table appear within the RTHS loop. To ensure accurate tracking of the desired acceleration, a model-based shake table control strategy is used, based on a linearized model of the shake table [5].

4. Experimental Setup

The proposed RTHS procedure is developed and verified using a large-scale bi-directional shake table. The setup consists of a large-scale shake table, a base-isolated single-story specimen as the experimental substructure, and MR damper specimen in the isolation layer, and a control and data acquisition system. The equipment is located at Tohoku University.

4.1 Large-scale bi-directional shake table and sensors

The shake table used in this study is 3 m by 3 m, driven by two actuators in X-direction and one actuator in Y-direction. The stroke is ±50 mm in X-direction and ±150 mm in Y-direction. The shake table has a maximum payload of 10 metric tons. The shake table is depicted in Fig. 1(b). The control hardware for the RTHS consists of a dSPACE DS1103 Controller Board. The sensors include accelerometers, load cells, and laser displacement transducers.

4.2 Shake table identification

A shake table transfer function model was determined using a 0-5 Hz band-limited white noise voltage command to the shake table and measured table acceleration. Fig. 4 shows the experimentally measured transfer function of the shake table along with the identified model. During identification, the base-isolated single-story experimental specimen is mounted on the shake table to include the effects of control-structure interaction (CSI) [8, 9]. The CSI in this study is observed to be very small as no specimen dynamics are immediately apparent in the measured transfer function. Although the specimen weighs 5 metric tons compared to the maximum payload of 10 metric tons, the base-isolation layer leads to a very small restoring force and thus small interaction between specimen and table. A good model is identified using 2 poles and 2 zeros, shown in Eq. (1).

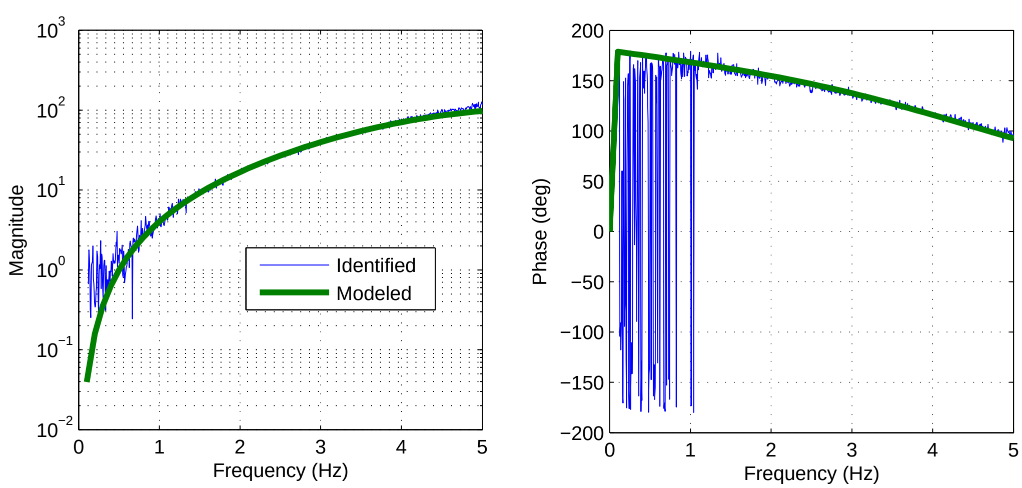


Fig. 4 – Transfer function magnitude of shake table with experimental specimen

$$G_{au}(s) = \frac{103.4515s^2}{s^2 + 33.12s + 1036} \tag{1}$$

4.3 Controller development

A feedforward controller (FF), designed to compensate for the linear dynamics of the shake table, is created as an inverse of the identified shake table model. In this study, the FF controller alone is found to be effective and sufficient to regulate the shake table performance because the shake table is accurately described by the identified linear model and also the base-isolated structure leads to very small CSI. Therefore, feedback control was not needed for this study. Shake table control details as applied to acceleration tracking can be found in [10].

4.4 Earthquake ground motions

Two well-studied earthquake ground motion records with different magnitudes and frequency content are selected as the input to the structure [11]: (1) El Centro: The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940, and (2) Kobe: the N-S component of the Japanese Meteorological Agency station during the Kobe earthquake of January 17, 1995. The reference earthquakes are passed through a 2-pole Butterworth high-pass filter with a cutoff frequency of 0.25 Hz. This pre-filtering removes the low-frequency behavior without altering the desired frequency content to avoid significant shake table drift, a challenge even for shake table RTHS. The earthquake records are scaled down during RTHS due to the stroke limitation of the shake table.

5. Favorable RTHS Stability for Base-isolated Specimens

One of the challenges for RTHS is that it requires a small, fixed sampling time in execution of each cycle. Moreover, unless properly compensated, time delays and time lags introduced by the experimental equipment can lead to stability and accuracy problems. Horiuchi et al. [12] demonstrated that for a linear-elastic, SDOF system, the effect of the energy introduced by a time delay is equivalent to negative damping. The negative damping was shown to be not only related to the time delay T_d, but also related to the stiffness of the specimen k^E. The equivalent damping added by the delay and stiffness is given as $-k^E T_d$. Therefore, negative damping can be especially problematic for steel frames and shear walls, which exhibit high stiffness and low structural damping. When negative damping exceeds the inherent structural damping of the system, the RTHS loop can become unstable.

Inter-story isolation, however, has a relatively low natural frequency (i.e., low stiffness). Delays in the desired response at lower frequencies have a smaller impact on the stability of the RTHS. Furthermore, the base shear of base-isolated specimens is small compared to traditional structural systems. Thus, the relative influence of the experimental substructure on the total structural is smaller, a favorable condition for RTHS stability. Also, there is in general a significant amount of damping in the isolation layer which can overcome stability problems due to negative damping.

To illustrate the favorable behavior of base-isolated specimens in RTHS, a purely numerical simulation of substructure RTHS is investigated. Two total structures are considered, one with a base-isolated upper substructure and one with a fixed-base upper substructure. The lower substructures are same and chosen as the first nine stories of the prototype structure. The base-isolated upper substructure is equal to that of the prototype structure without supplemental damping in the isolation layer. The fixed-base upper substructure has a stiffness adjusted to achieve 4.81 Hz, the same natural frequency of the upper stories of the target structure without inter-story isolation. The damping of both upper substructures is taken as 2.4% to avoid favorable bias toward a more highly damped system. Both total structures are subject to the 50% El Centro record with varying levels of simulated delay in the RTHS loop.

Table 1 summarizes the time delay tolerance on maximum and RMS base shear of the experimental substructure with and without isolation. The base shears are much lower in magnitude for the experimental substructure with isolation, resulting in much larger time delay tolerance. Fig. 5 shows the time histories of the base shear for the two structures with different level of time delay. From Fig. 5, the structure without inter-story isolation can only tolerate a 5 ms delay and becomes unstable when T_d reaches 10 ms. With inter-story isolation, the structure has a larger tolerance on time delay up to 50 ms without compromising the accuracy significantly. The system remains stable even as the time delay approaches ten times larger than the tolerance of the structure without isolation, though accuracy is compromised. This simple numerical study clearly demonstrates favorable behavior of base-isolated specimens in RTHS.

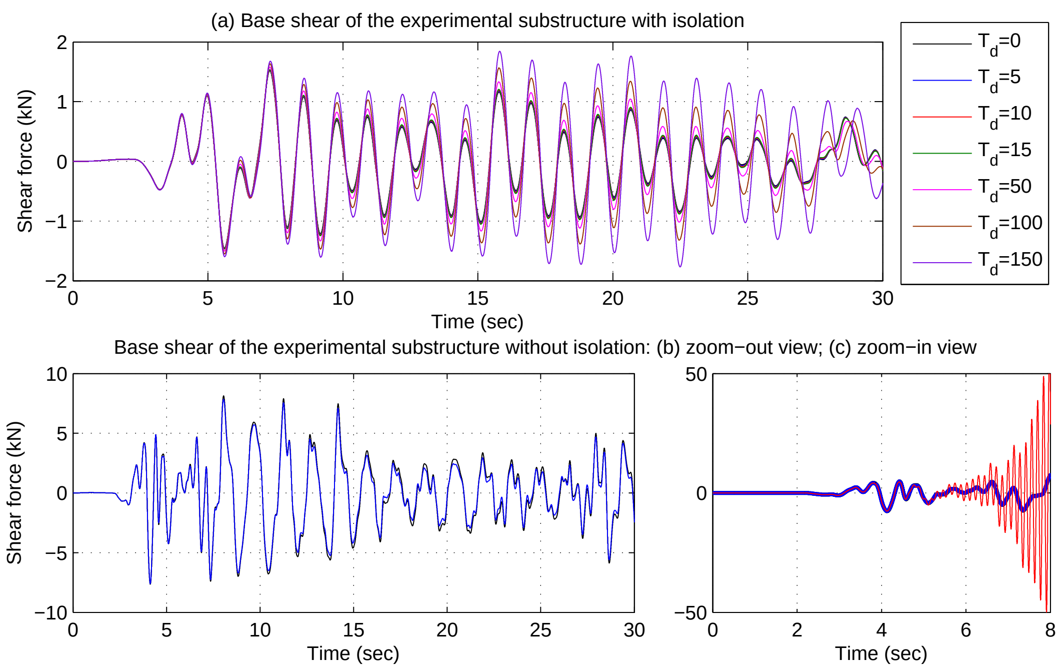


Fig. 5 – Influence of time delay on time histories of base shear of experimental substructure with or without seismic isolation

Table 1 – Base shear of the experimental substructure

Time delay (ms)	Structure with inter-story isolation		Structure without inter-story isolation	
	Max (kN)	RMS (kN)	Max (kN)	RMS (kN)
0	1.5184	0.4490	8.1215	2.3386
5	1.5245	0.4527	7.8268	2.1715
10	1.5304	0.4565	3.05×10^{27}	1.86×10^{26}
15	1.5363	0.4605	Unstable	
50	1.5778	0.4955		
100	1.6337	0.5742		
150	1.8446	0.7103		

6. Performance of RTHS and Inter-story Isolation

This section investigates the performance of the proposed RTHS technique, focusing on the tracking of the desired acceleration signal at the interface DOF and achieving accurate RTHS performance when compared to numerical simulations. In addition, the benefits of inter-story isolation as a structural design alternative are demonstrated. All time-domain measurements are passed through a low-pass filter with a cutoff frequency of 8 Hz in post processing. The results and conclusions are based on the inter-story isolated structure with passive-on MR damper unless otherwise explicitly stated. For traditional shake table tests, the structure is the physical base-isolated specimen. For the RTHS, the structure is the prototype structure divided into numerically simulated lower stories and experimentally evaluated upper stories represented by the base-isolated specimen.

6.1 Acceleration tracking performance

Acceleration tracking performance of the FF controller is presented herein for accelerations determined both offline and online. Fig. 6 shows the acceleration tracking performance of the FF controller in traditional shake table testing with the experimental specimen excited by 100% El Centro records. Analysis in both time domain and frequency domain demonstrate excellent reproduction of the desired predefined ground motions. During RTHS, the shake table will track the absolute acceleration of the interface DOF (i.e., the 9th floor). Fig. 7 shows the online acceleration tracking performance of the interface DOF during RTHS when the prototype structure (10-DOF) is subjected to 50% El Centro earthquake. Through the developed FF controller, excellent tracking performance is observed regardless of whether the desired acceleration is determined online or offline. Because the shake table is accurately described by a linear model and the CSI is very small, FF control alone provides adequate tracking and no additional controller improvements are necessary.

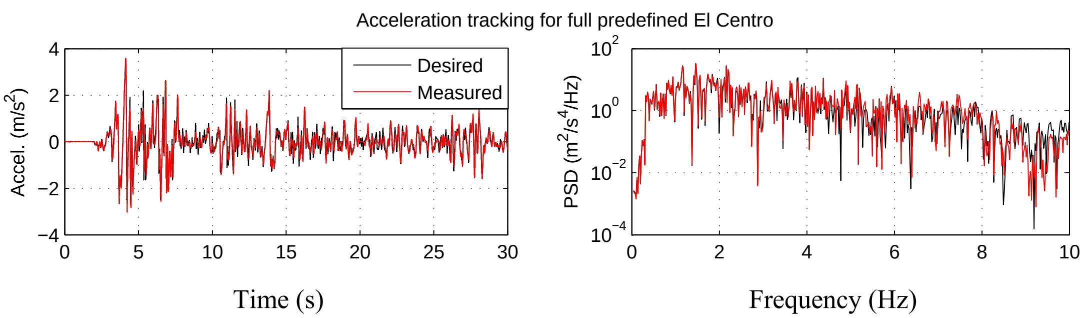


Fig. 6 – Acceleration tracking performance during RTHS

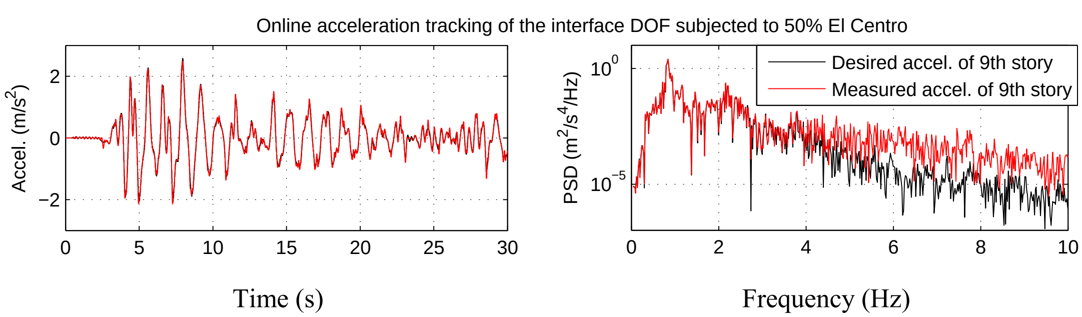


Fig. 7 – Acceleration tracking performance during RTHS

6.2 Performance of RTHS

In this section, the performance of the proposed RTHS approach is presented for the inter-story isolated structure with passive-on MR damper subjected to 50% El Centro and 20% Kobe record. Reference numerical simulations include the phenomenological MR damper model to represent MR damper behavior. The two cases for comparison are listed as below:

1. Numerical simulation of the 10-story structure with passive-on MR damper (SIM); and
2. RTHS of the 10-story structure with a 9-DOF numerical substructure, a SDOF experimental substructure, and passive-on MR damper (EXP-RTHS).

Fig. 8 shows the time histories of the absolute accelerations and interstory drifts for the inter-story isolated structure. The RTHS approach performs well not only on the peak responses but also throughout the entire time history, matching well with the numerical simulation. Fig. 9(a) shows the time histories of the passive-on MR damper forces for the total structure subjected to 50% El Centro and 20% Kobe earthquakes. The numerical MR damper model can generally represent the dynamic behavior of the long-stroke MR damper used in RTHS tests. The match is further confirmed by the hysteresis loop shown in Fig. 9(b) for the total structure subjected to 50% El Centro and 20% Kobe earthquakes.

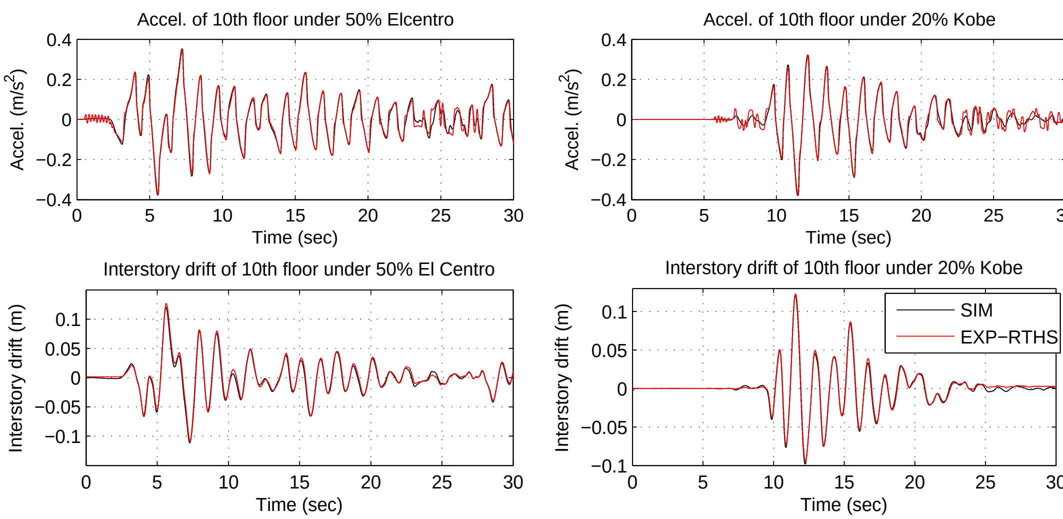


Fig. 8 – RTHS performance of absolute accelerations and interstory drifts

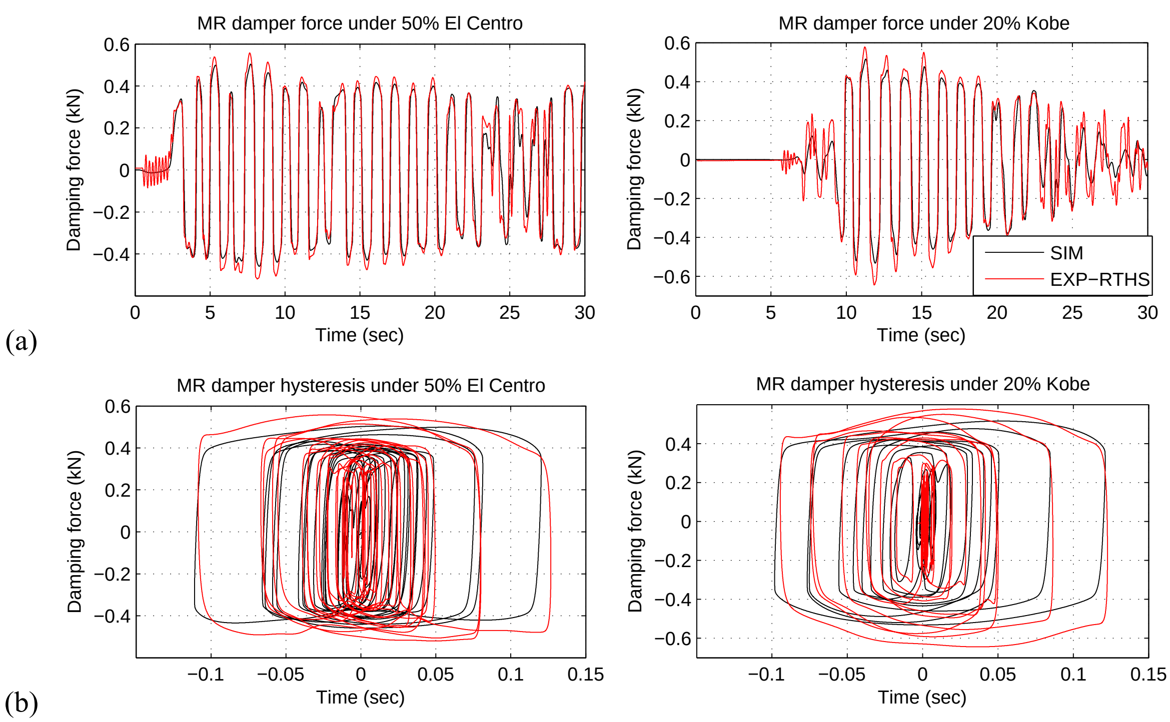


Fig. 9 – RTHS performance of (a) MR damper forces; (b) MR damper hysteresis.

6.3 Performance of inter-story isolation

This section investigates the structural responses of the total structure with inter-story isolation through RTHS. Fig. 10 shows the absolute accelerations and interstory drifts of the total structure with passive-on MR damper subjected to 50% El Centro earthquake. It can clearly be seen that the acceleration of the upper story above isolation (e.g., story 10) is much lower in amplitude, while the interstory drift is much larger than lower stories, as expected.

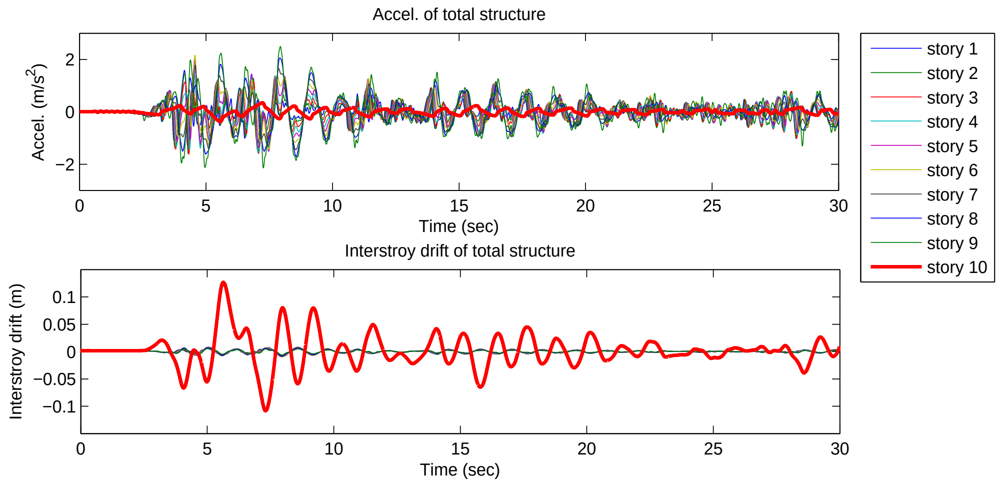


Fig. 10 – Absolute accelerations and interstory drifts of the total structure

The benefits of inter-story isolation for high-rise buildings, assumed herein as a retrofit technique, are further confirmed by comparing the base shear demands with a 9-story structure (i.e., un-retrofit) and a 10-story structure without inter-story isolation (e.g., retrofit with a traditional structural system). The three structures studied are shown in Fig. 11. Both 9-story structure and 10-story structure without inter-story isolation were analyzed in numerical simulation.

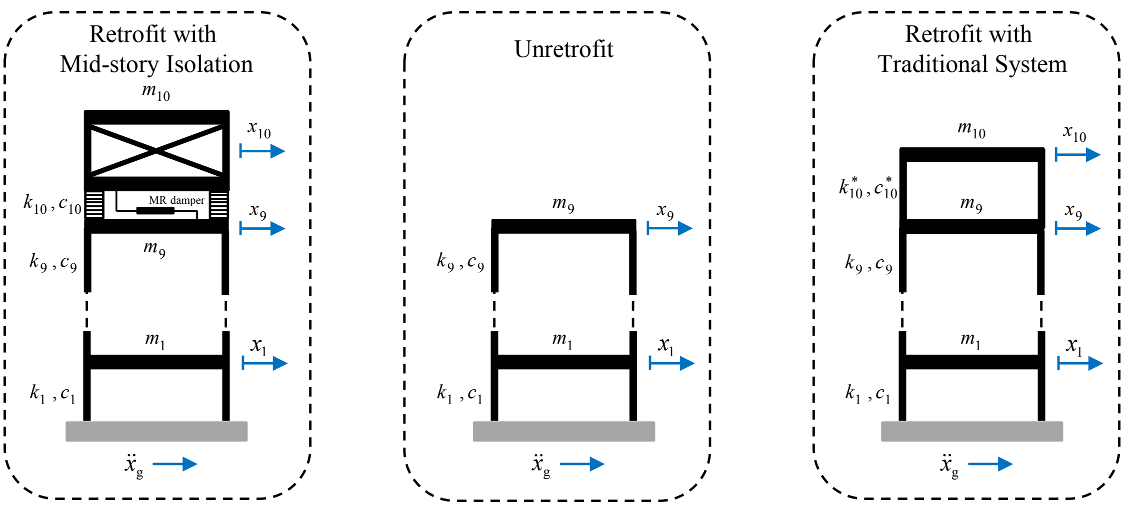


Fig. 11 – Structure systems for investigation.

One benefit of implementing inter-story isolation is for retrofit applications. By using inter-story isolation, the accelerations of the extra floors can be greatly reduced, allowing additional floors to be built on an existing structure without increasing the base shear demand. This benefit is demonstrated by comparing an unretrofit 9-story structure, a 10-story structure retrofit without inter-story isolation, and a 10-story structure retrofit with inter-story isolation. Fig. 12 shows the base shear of the original structure and both retrofitted structures. The base shear is reduced by the inter-story isolation not only on the peak responses but also throughout the entire time histories. Although similar performance observed for 10-story structure without inter-story isolation, the mechanism behind the base shear reduction is different. Through inter-story isolation, the entire structure nominally decoupled into two substructures and the lower substructure behaves similar to the original structure, especially in higher modes (shown in Fig. 13). For the 10-story structure without inter-story isolation, the natural frequency is decreased from 0.81 Hz to 0.64 Hz by adding the 10th floor. The influence on lower stories is large because the 10th floor actually represents five upper stories of the target model of the IFB. The entire structure, including the 10th floor, behaves as one structure with a lower first natural frequency, protecting it from the frequency content of the input ground motions. Fig. 13 shows the mode shapes of the original structure and two retrofitted structures. Since the isolation adds a lower mode to the entire structure, the mode shapes of the retrofitted structure with inter-story isolation are shifted one mode below to be comparable to the original structure and retrofitted structure without inter-story isolation. Through the proposed RTHS techniques, the responses of high-rise building with inter-story isolation are investigated, and the benefits of the inter-story isolation are demonstrated.

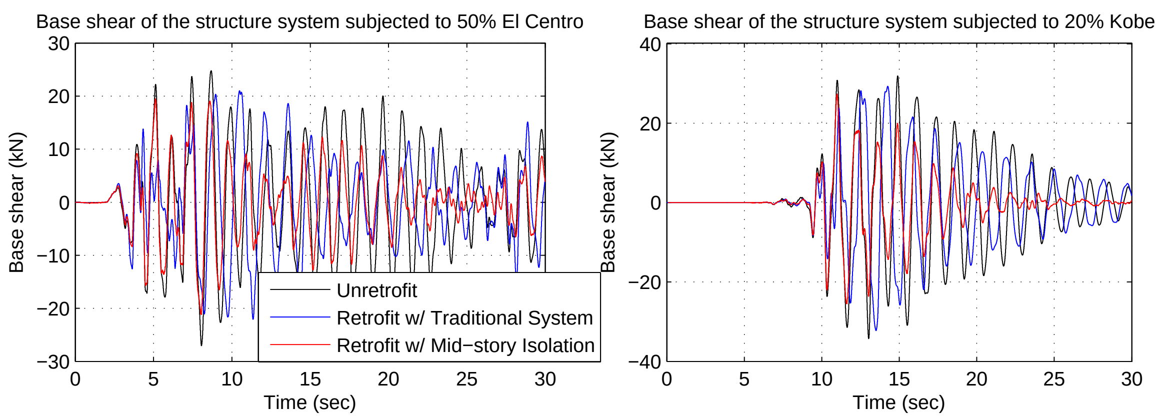


Fig. 12 – Base shear of the original structure and retrofitted structure with passive-on MR damper

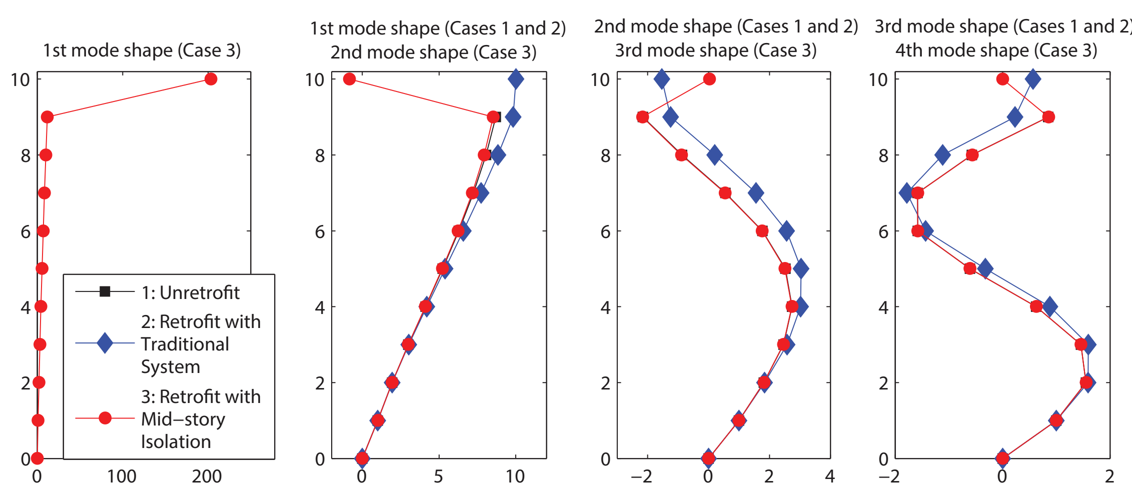


Fig. 13 – Mode shapes of the original structure and two retrofitted structures.

6. Conclusions

This paper investigates the seismic performance of a 14-story high-rise building with inter-story isolation through shake table RTHS. The substructure below inter-story isolation is simulated numerically while the superstructure including inter-story isolation is tested experimentally. Shake tables provide an excellent tool for substructure RTHS due to their widespread availability and ease of creating and enforcing interface boundary conditions for certain structures.

The proposed RTHS techniques were validated using a large-scale shake table and a base-isolated specimen. The proposed strategy for shake table control was verified to offer good acceleration tracking performance. The effectiveness of the overall RTHS in reproducing the total structural behavior was verified through comparisons with numerical simulations. This confidence will enable studies of inter-story isolation systems and supplemental damping which may not be as easily modeled numerically.

The benefits of inter-story isolation for retrofit were confirmed through RTHS. Base shear is maintained at low levels relative to the structure before retrofit. Furthermore, the stories above the isolation layer exhibit very low levels of acceleration. Inter-story isolation is shown to be an attractive alternative to traditional structural systems, creating nominally decoupled systems with large architectural and structural design freedom.

7. Acknowledgements

This material is based upon work supported by the US National Science Foundation under Grant No. 1444160 and by the Japan Society for the Promotion of Science under Grant-in-Aid for Scientific Research (B) No. 15H04070. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of these agencies.

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