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MODEL LATERAL SUPPORT SYSTEMS UNDER SEISMIC LOADING FOR EARTHQUAKE ENGINEERING EDUCATON

Aparjeet S. Rangi[1] Ali Porbaha[2]

ABSTRACT

Lateral support systems are commonly used to strengthen the structures against sideway forces caused by ground motions during an earthquake. The two most commonly used lateral support systems are Moment Resistant Frames and Cross Bracing Frames. The objective of this study is to develop scaled physical models and compare the responses of the lateral support systems under several dynamic/earthquake loading conditions using a shake table. The natural frequency, maximum accelerations, and damping characteristics of the models are measured and compared for both free vibration and forced vibrations using Sweep loading and Northridge earthquake. Overall, these lateral support systems experimentally determine the level of relative improvement in dynamic response of the model systems by reducing lateral acceleration and increasing the damping of the systems and thus providing more resistant during seismic events. The details of the equipment design and experiments are presented in this paper. These models and experiments could be used as an educational tool for earthquake engineering courses in undergraduate and graduate levels.

Introduction

The ground motion generated during an earthquake impacts the behavior of natural and manmade systems. The extent of the earthquake damage can be controlled and/or mitigated by applying structural systems capable of impeding the shaking. Lateral support systems are commonly used to strengthen the structures against sideway forces during an earthquake. The two most commonly used lateral support systems are Moment Resistant Frames and Cross Bracing Frames. From the educational viewpoint it will be desirable to physically demonstrate the level of improvement these lateral support systems have in comparison to the behavior of a system with no lateral support mechanism.

The objective of this study is to develop physical models and compare the responses of the lateral support systems exposed to several dynamic/earthquake loadings using a shake table. The lateral support systems include Base Frame (no lateral support system), Moment Resistant Frame and Cross Bracing Frame. The natural frequency, maximum accelerations, and damping

[1] Graduate student and [2] Faculty, Department of Civil Engineering, California State University, Sacramento, 6000 J Street, Sacramento, CA 95819-6129, aparjeet1@yahoo.com , Porbaha@ecs.csus.edu

characteristics of the models are compared. These models and experiments could be used as an educational tool for earthquake engineering courses in undergraduate and graduate levels. The details of the equipment design and experiments are presented below.

Materials Used

All three models are designed as a signal degree of freedom system. The base and top plates of the models are fabricated from clear Acrylic plastic, commonly known as Plexiglass. The dimensions of base and top plates are 4.25 in by 12 in (108 mm by 305 mm) and the thickness is 0.5 in (13 mm). The columns are fabricated from Acrylonitrile Butadiene Styrene (ABS). The dimensions of columns are 4.25 in by 19.75 in (108 mm by 502 mm) and the thickness is 0.20 in (5 mm). All three models are designed to incorporate the limitations of space in the laboratory, size of the shake table, and the materials cost.

Connections of Lateral Support Systems

The basic frames for all three models are identical. Columns are bolted to the top and bottom plate using Stainless Steel Allen Head Cap Screws, 8-32 by 1.0 in (25 mm) long. Major differences lie in the detailing of each model joint. Figure 1 shows the schematic diagram of three model frames, as described below:

(a) Base Frame: The model does not have any lateral support system. Therefore, it has no additional component.

(b) Moment Resistant Frame: The model has additional components attached to the basic frame. Steel angles of 2 in by 2 in by 0.25 in (51 mm by 51 mm by 6 mm) are bolted on the inside of all four corners of the model. In addition to the inside steel angles, a rectangular steel plates size of 3 in by 2 in by 0.25 in (76 mm by 51 mm by 6 mm) are connected on the outside of all four corners of the model. The outside steel plates are connected in such a manner so that their edges are aligned with the inside steel angles, thus making the model symmetric. The purpose of steel plates and steel angles is to make the corners of the model rigid in order to ensure that angle of all the corners remain 90 degrees during lateral load testing.

(c) Cross Bracing Frame: The model has additional components attached to the basic frame. Small steel angles with protruding edge are connected to the inside of all four corners of the model. Nylon coated tow wire with a strength of 60 lbs (27 kg) used as cross bracing is connected to these steel angles. Two wires are connected diagonally, to form a cross bracing. The wires passed through the hole in the center of the steel angle, looped and joined by clevis. This connection ensured that the bracing is at the edge of the model. Turnbuckles with a hook and an eye end are also connected to the diagonal wires at the top two corners to adjust the tension of the wires.

Components

Figures 1 and 2 show the model frames and the experimental setup. All three models (Base, Cross Bracing, and Moment Resistant frame) are bolted to plexiglass base plate. The whole module is mounted on the shake table. This set up would have allowed all three models tested simultaneously during lateral loading but due to the limitation of resources, it was not feasible. Therefore, instead of testing all three models simultaneously, two separate experiments are performed; the Base Frame versus Moment Resistant Frame, and the Base Frame versus Cross Bracing Frame. Each model has an accelerometer attached at the top that measured the acceleration at the top of the model during testing. The accelerometer on the base plate measures the ground acceleration. A Data Acquisition System (DAS) recorded the data from the accelerometers.

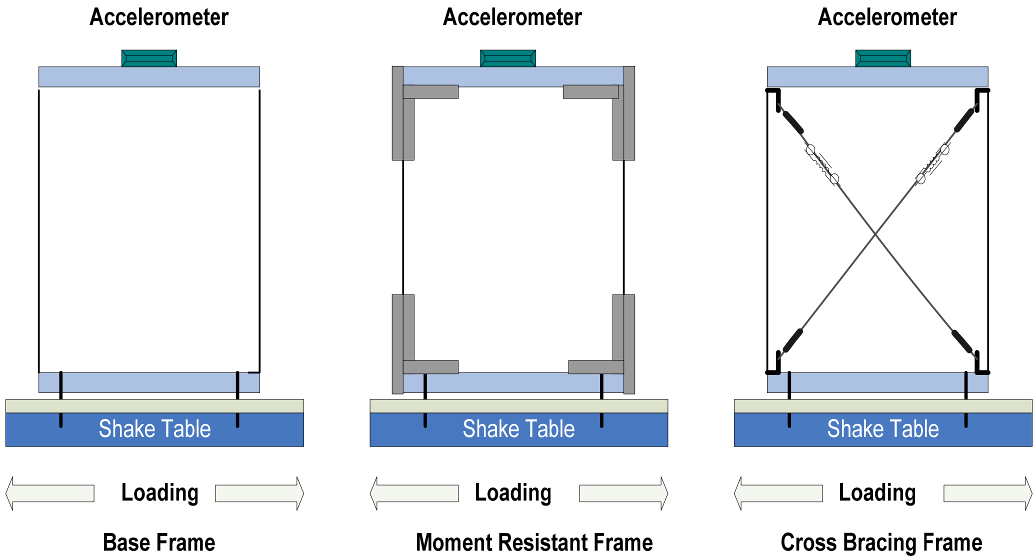

Figure 1: Schematic Model Frames

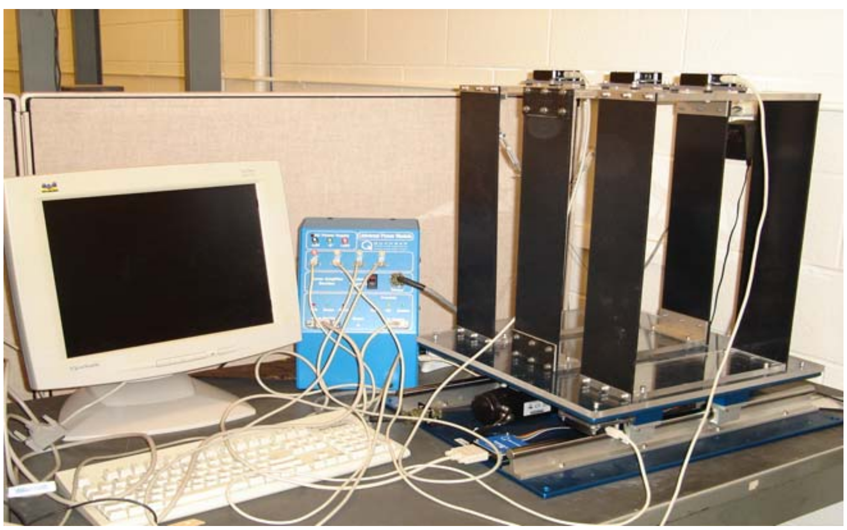

Figure 2: A View of Experimental Setup

Free Vibration

The first sequence in the experimental testing is to get the response of the models under free vibration. An equal drift is applied at the top of the models. The force is released and the models are allowed to oscillate until their natural damping brought them to stop. The accelerometers recorded the acceleration experienced by each model. Further analysis is done using MatLab to calculate the frequency response of the models and other characteristics. The responses of these models under free vibration are presented in Figures 3 and 4.

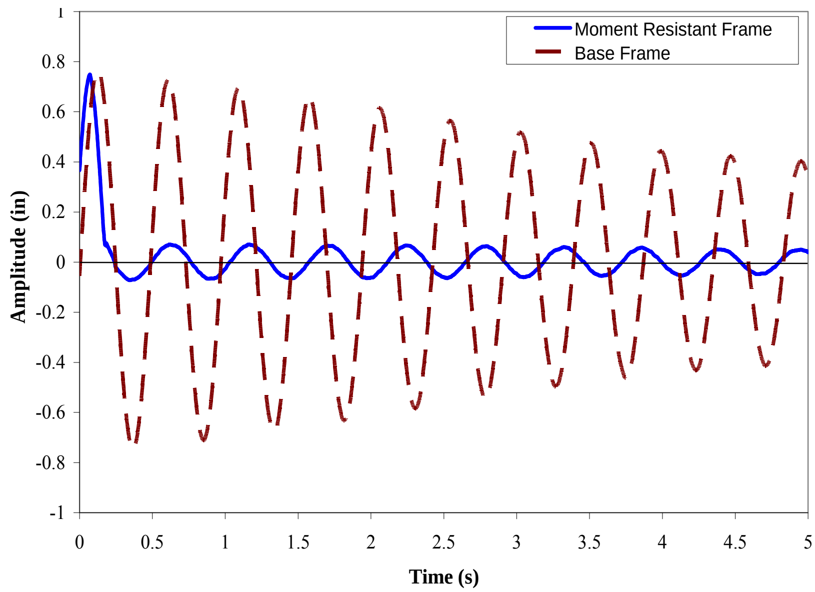

Figure 3: Responses of Base Frame versus Moment Resistant Frame under Free Vibration (1 in=25 mm)

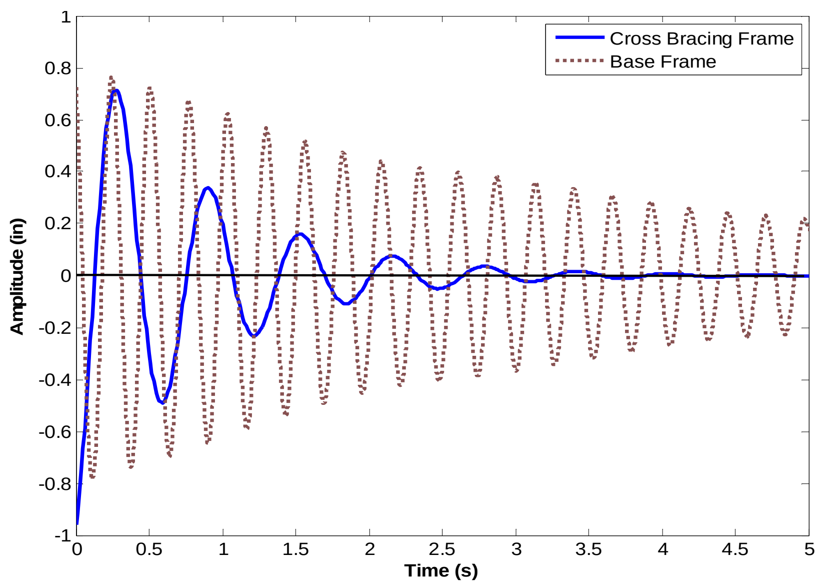

Figure 4: Responses of Base Frame versus Cross Bracing Frame under Free Vibration (1 in=25 mm)

Forced Vibration

The second sequence of experiments is the forced vibration of the models. Two types of loading included; (a) Sweep loading by gradually increasing the accelerations and (b) Northridge earthquake loading. The acceleration and responses of all the models for these loadings are presented in Figures 5 to 8.

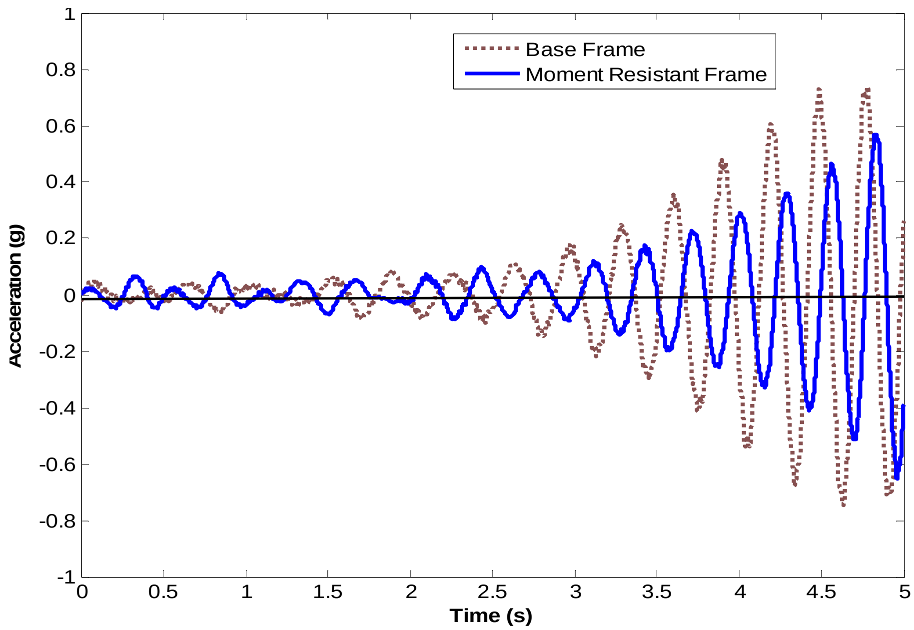

Figure 5: Responses of Base Frame versus Moment Resistant Frame under Sweep loading

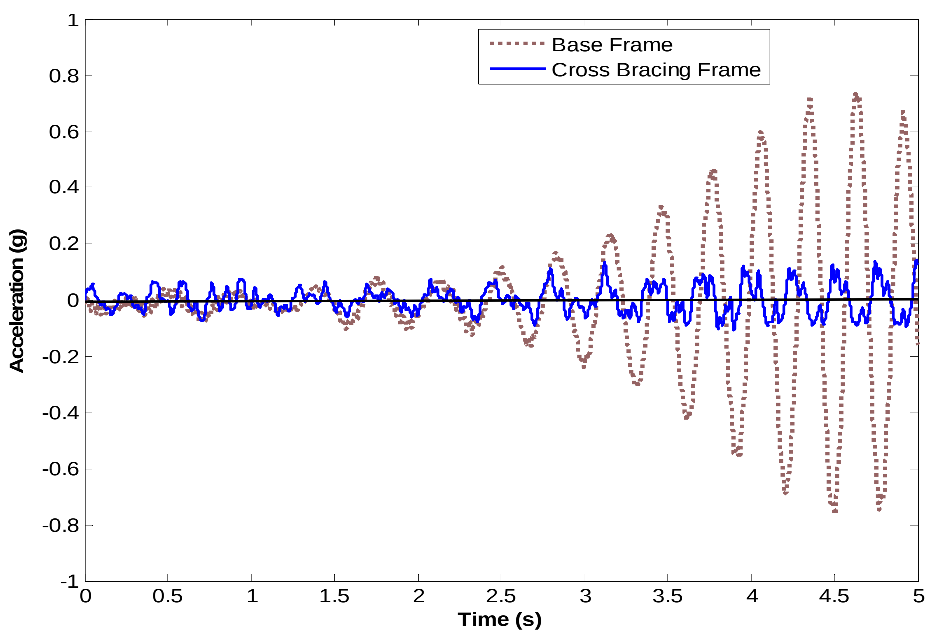

Figure 6: Responses of Base Frame versus Cross Bracing Frame under Sweep loading

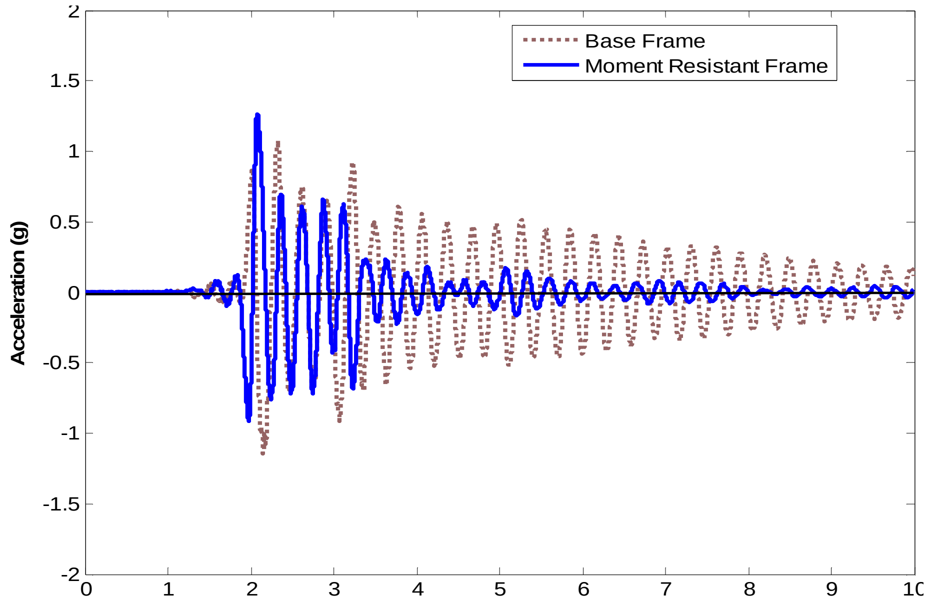

Figure 7: Responses of Base Frame versus Moment Resistant Frame under Northridge earthquake loading

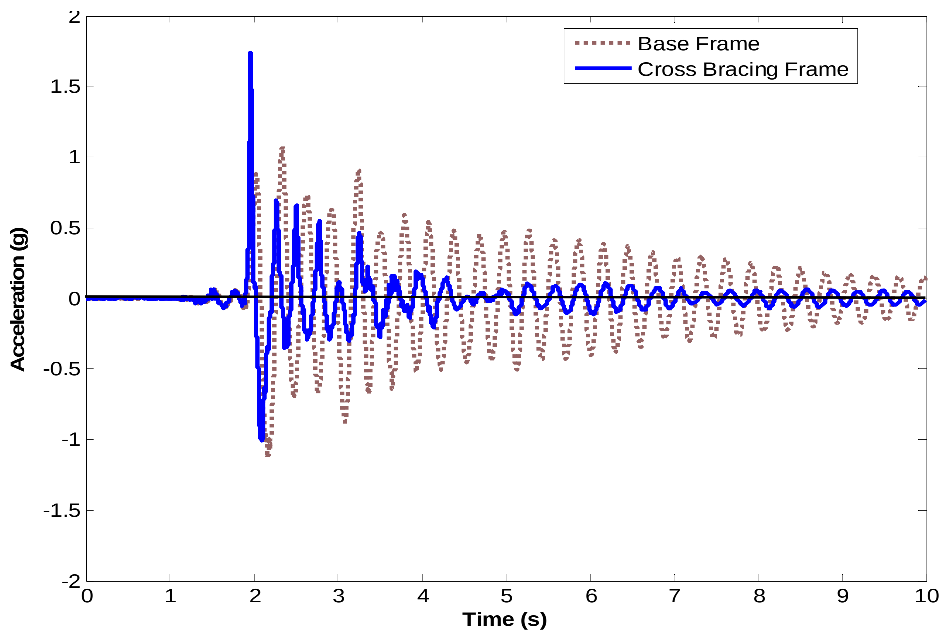

Figure 8: Responses of Base Frame versus Cross Bracing Frame under Northridge earthquake loading

Estimation of Damping

The damping obtained from a second order differential equation for free vibration of a single degree of freedom system is classically defined as (Chopra, 1995, Clough and Penzien, 1993):

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = 0 \tag{1}$$

where; m = mass of the system, c = damping coefficient, k = stiffness and x(t) = displacement. The damping ratio of the system is estimated using "Half-Power" Bandwidth method. Bandwidth defined as the difference between two frequencies corresponding to the same response amplitude. In the evaluation of the damping, it is convenient to measure the bandwidth at $1/\sqrt{2}$ of the peak amplitude (Paz and Leigh, 2004). In Bandwidth method, damping is calculated by taking arbitrarily first point, x_1, and second point is taken as $x_1/2$. By using equation of the envelope for damped motion under free vibration, damping is:

$$\beta = \ln 2 / (2\pi N) \tag{2}$$

where N is number of periods between x_1 and $x_1/2$, N could be an integer.

Numerical Simulation

Numerical simulation of the physical models was performed using Simulink. Simulink incorporates the library of models into a block diagram and evaluates block parameters, data types, and sample times. Using the same data for simulation as in the physical testing Simulink characterized the responses similar to the physical models for sine Sweep loading for models under forced vibration (Rangi, 2008). The details of numerical simulation are not presented here due to length limitation of the conference proceedings.

Results and Discussion

Tables 1 and 2 show the summary of results for all models tested in this study. The free vibration response spectra shows a significant increase in damping with the lateral support systems, i.e. Moment Resistant and Cross Bracing as seen in Figures 3 and 4, compare to the Base Frame. The damping calculated using Eq. 2 shows that the Moment Resistant Frame's damping increased by approximately 1.6 times and the Cross Bracing Frame's damping increased by approximately 16 times compare to the Base Frame. This means that the Moment Resistant Frame decayed almost twice the Base Frame and the Cross Bracing Frame decayed almost 16 times the Base Frame.

From the forced vibration, as shown in Figure 5 and 6, the responses of lateral support systems under Sweep loading shows a significant decrease in spectral acceleration at the top of the models. The maximum acceleration experienced by the Base Frame versus Moment Resistant Frame is 0.74g and 0.55g respectively and for the Base Frame versus Cross Bracing Frame is

0.74g and 0.13g, respectively. This means, as expected, the lateral support systems resulted in decrease in acceleration for the Moment Resistant and the Cross Bracing Frames. There is approximately 26% decrease in acceleration for the Moment Resistant and approximately 82% decrease in acceleration for the Cross Bracing compared to the Base Frame.

From the forced vibration, as shown in Figures 7 and 8, the responses of lateral support systems under Northridge earthquake loading shows a significant decrease in spectral acceleration at the top of the models. Initially under forced vibration, lateral acceleration experienced by all the models was high due to the initial jolt by the Northridge Earthquake. However, immediately after the excitation, the lateral acceleration experienced by the Moment Resistant and the Cross Bracing Frames decreased significantly due to the lateral support systems built in the models. The maximum acceleration, after the initial jolt, experienced by the Base Frame versus Moment Resistant Frame is 0.92g and 0.68g respectively and for the Base Frame versus Cross Bracing Frame is 0.92g and 0.65g respectively. These results concluded that decrease in acceleration for the Moment Resistant and the Cross Bracing Frames is due to the lateral support systems. There is approximately 26% decrease in acceleration for the Moment Resistant and approximately 29% decrease in acceleration for the Cross Bracing compared to the Base Frame.

Table 1: Damping and Maximum Acceleration from Shake Table

	Max. Acceleration (g) [Forced Vibration] Sweep loading	Max. Acceleration [Forced Vibration] Northridge earthquake loading	Damping (β) [Free Vibration]
Base Frame	0.74	0.92	0.007
Moment Resistant Frame	0.55	0.68	0.011
Cross Bracing Frame	0.13	0.65	0.110

The calculated maximum accelerations of the models under Sweep loading are different from Northridge earthquake loading because Sweep loading is a sine loading with an increasing frequency whereas the Northridge earthquake loading is a scaled loading of the actual earthquake occurred in 1994 in California. However, the percentage decrease in the acceleration for the Moment Resistant Frame compare to the Base Frame, i.e. 26%, is the same under both the loadings. Whereas the percentage decrease in acceleration for the Cross Bracing Frame compare to the Base Frame is approximately 82% in Sweep loading and 29% in Northridge earthquake loading.

The period of the models is calculated by averaging the peak amplitudes of the free vibration response spectra. Based on the calculations, as shown in Table 2, the Base Frame has longer period/less frequency thus making it less stiffer compare to the Moment Resistant and the Cross Bracing. On the other hand, the Cross Bracing Frame has shorter period/higher frequency making it more rigid compare to the Base Frame and the Moment Resistant Frame. In other words, as expected, the Base Frame experienced greater lateral acceleration thus less resistant to seismic forces compare to lateral support systems. In addition, within lateral support systems, the Cross Bracing experienced less lateral acceleration thus more resistant to seismic forces compare to the Moment Resistant.

The variance in the response of the Cross Bracing Frame is due to the variance in the tension of the turnbuckles given at the time of the experiment. When the tension level of the turnbuckles is changed, the response will be different.

Table 2: Estimated Time Period and Frequency from Shake Table under Free Vibration

	Time Period (sec) [T]	Natural Freq. (Hz) [f]	Damped Natural Freq. (Hz) [f_d]	Circular Freq. (rad/sec) [ω]	Damped Circular Freq. (rad/sec) [ω_d]	Stiffness (lbs/inch) [k]	Damping Coeff. (lb-sec/inch) [c]
Base Frame	0.29	3.41	3.41	21.42	21.42	3.85	0.003
Moment Resistant Frame	0.27	3.78	3.78	23.75	23.75	6.67	0.006
Cross Bracing Frame	0.22	4.48	4.46	28.18	28.00	7.21	0.056

Concluding Remarks

The objective of this study is to model the concept of no lateral support system (Base Frame) versus two lateral support systems (Moment Resistant and Cross Bracing Frames) tested under several excitation levels using a shake table. The Sweep loading results show that the maximum acceleration experienced by the Base Frame versus Moment Resistant Frame is 0.74g and 0.55g, and for the Base Frame versus Cross Bracing Frame is 0.74g and 0.13g, respectively. Under Sweep loading, there is approximately 26% decrease in acceleration for the Moment Resistant and approximately 82% decrease in acceleration for the Cross Bracing compare to the Base Frame. Furthermore, the Northridge earthquake loading results show that the maximum acceleration experienced by the Base Frame versus Moment Resistant Frame is 0.92g and 0.68g and for the Base Frame versus Cross Bracing Frame is 0.92g and 0.65g, respectively. Under Northridge earthquake loading, there is approximately 26% decrease in acceleration for the Moment Resistant and approximately 29% decrease in the Cross Bracing compare to the Base Frame. In terms of damping, the decay in Moment Resistant Frame is almost twice the Base Frame, and almost 16 times in the Cross Bracing Frame. In terms of period, the Base Frame is obviously longer compare to both the Moment Resistant and Cross Bracing Frames.

Overall, based on the experiments performed for the models the lateral support systems demonstrated a significant improvement in dynamic response of the model structures by reducing the lateral acceleration and increasing the damping of the systems. These results are based on the specific tension of the turnbuckles in the Cross Bracing Frame at the time of the experiment. Obviously, when the tension level is varied, the results could be different.

The next step will be to incorporate these models and the experiments into earthquake engineering courses in which the second author teaches in undergraduate and graduate levels. The feedback from the students will help in understanding how the models and the experiments will contribute to student learning of earthquake engineering concepts.

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