Shake Table Acceleration Tracking Performance Impact on Dynamic Similitude - Preliminary Findings

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SUMMARY
Dynamic simulations conducted on shake tables offer an economical means of examining the inelastic response of structures to earthquakes. Past studies have shown the inability of shake-tables to precisely simulate earthquake records. While such performance deficiencies are well documented, their influence on the inelastic response of models has not been directly studied. The objective of this research is to establish how errors associated with earthquake tracking performance influence inelastic responses, and to identify the key parameters that affect such influences. Simulated earthquake records (with acceleration tracking errors) were obtained from a unidirectional shake-table and used within a parametric study that had variables of (1) earthquake record (simulated versus Input), (2) scale, (3) frequency, (4) non-linearity. Results indicated that a) the inability of shake tables to replicate the input signal at small physical scales resulted in error between 50 and 65% b) Nonlinear energy dissipation obtained thru simulations of FE model replicas of the physical models shows the shake-table simulated is not linearly proportional to the actual signal.

Keywords: Dynamic similitude shake table performance

1. INTRODUCTION

Dynamic simulations conducted on shake tables offer an economical means of examining the inelastic response of structures resulting from simulated earthquake events. While there have been many such studies since the mid-seventies that have contributed to the understanding of the earthquake response of structures, there are also several sources of uncertainty that plague the reliability of such studies. Principal among these is the fact that shake-tables are not able to precisely replicate the actual earthquake record (Bertero et. al.) (Blondet et. al.) (Clough et. al.) (Gergeley et. al.) (Gulkan et. al.) (Li et. al.) (Manos et. al.) (Mills et. al.). Specifically, past studies have shown that the acceleration tracking performance of uni-axial shaketables can have errors as large as 30 to 60% compared to the desired signal as measured based on differences in amplitude using RMS (Root-Mean-Square) Error (Luco et. al.). Bertero reported errors as high as 22% between the shake table simulated signal and the input signal when testing a 5 story 1/7th scale reinforced concrete structure on the Berkeley shake table. The error was reported based on differences in amplitude. Such errors are likely caused by many different factors, but key influences identified in the literature are related to (1) the control schemes that are based on acceleration signals, (2) model-table interaction (which tends to affect larger scale studies due to the relatively large mass), and (3) high frequency content (which tends to affect smaller scale studies due to the scaling of time).

Although the inability of shake tables to precisely replicate earthquake records is well established, the influence of such errors on the inelastic response of models remains uncertain. In the past studies on shake tables, oftentimes distortions in dynamic similitude were justified primarily as it relates to scaling mass. To achieve true dynamic similitude requirements; additional mass required for similitude would have to be evenly distributed on the model; however, this requirement is practically impossible to achieve due to limitations associated with size, boundary conditions such as connections and potential distortion of the model stiffness as a result of adding mass where it may adversely affect the model response. As a result, past scaled model research has relied on achieving "adequate" dynamic similitude thru "lumping" the scaled mass typically at the floor level while ensuring that the lumped mass does not adversely affect the stiffness in the model. Ideally, achieving "true" dynamic similitude would isolate any differences in response due solely to the shake table; however, this objective has been viewed as unrealistic in past research. The use of a centrifuge to simulate accelerations is a plausible scenario since it would preclude the need to scale mass and although this is a practical scenario in geotechnical testing; is not yet a practical solution to test building structures.

While the earthquake engineering research community has recognized any distortions in similitude due to mass, there are additional violations in similitude the impacts of which have not been studied or even discussed. A horizontal shake table represents a platform that may be envisioned as the interface between foundation and firm soil and rock. It is often assumed that the acceleration time-history output of the table simulates how ground motion shakes a building. The complex kinematics that actually take place between a foundation and soil or rock during an earthquake - which regulates the energy that is input from the ground into a structure, is seldom measured, understood or simulated. Unless a building has a rigid raft foundation, differential movements and rotations and especially uplift at the soil interface are known to be highly critical parameters impacting energy input. A shake table will have pitch, roll and yaw responses in addition to three translations, some of which would be controlled and some of which would be restrained but not entirely eliminated. It follows that it is not possible to envision dynamic similitude during an earthquake unless the kinematics at the model-table interface may be controlled as a variable.

The consequences of errors in simulating the kinematics at the foundation-soil interface, or those in the tracking performance of a uniaxial shake table have not been discussed in past research. The objectives of the research reported herein is to establish: (a) evaluate any differences in the dynamic properties of models as measured on a rigid floor as opposed to on a shake table; (b) Determine the extent to which errors associated with earthquake tracking performance impact dynamic similitude; (b) how these errors influence inelastic responses, and, (c) to identify the key parameters that affect such influences. By examining critical responses that govern the earthquake response of structures (such as story drift, base shear, energy dissipation, etc.) this study aims to understand the relevance of shake table errors.

2. RESEARCH PROGRAM

To establish the relevance of shake table errors on the inelastic building response the following research tasks were performed (Figure 1):

- Design and construction of three physical models representing a low-rise building prototype at three different scales.
- Free vibration testing of the three physical models rigidly anchored on the lab floor as well as anchored on the shake table.
- Tuning of the shake table PID (Proportional-Integral-Derivative) controller
- Earthquake simulations as a) bare table and b) with physical models located in the middle and along the edge to establish influence of the physical models on the shake table response, conducted for each physical scale.
- Parametric study using finite element models (at each scale) to examine the inelastic response of the models due to the shake table errors across several story heights and capacity to demand (C/D) ratios.

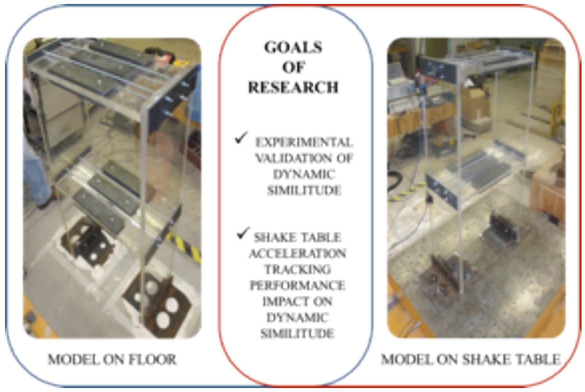

Figure 1. Goals of the Research

3. PHYSICAL SCALED MODEL DESIGN AND CONSTRUCTION

The experimental program was based on a scenario that consisted of constructing a pseudo-prototype physical scaled model representative of a two-story full-scale structure and then building two additional physical models that were scaled from the pseudo-prototype. The prototype structure was selected to have a fundamental natural frequency of 2 Hz; typical of a structure built with light framing that can be idealized as a shear building. The pseudo-prototype model was constructed by scaling the prototype frequency. The geometric and lumped mass properties were proportioned to satisfy dynamic similitude (Figure 2) and the two additional physical model were constructed at 1/3 and 1/2 scale of the pseudo-prototype, respectively. The mass and dimensions of the smaller physical models were scaled directly from the pseudo-prototype. The properties of the physical models are shown in Table 1. As shown, the scaled length of the physical model is determined by dividing the dimension of prototype by the scale factor, (L_p/L_r). The "lumped" mass of the model is determined by dividing the mass of the prototype by the squared of the scale factor, (M_p/L_r^2).

Table 1 – Dynamic Similitude Properties of "Scaled" Physical Models

Model Scale	Length	Mass				
	Scale Factor	Scale Factor	Total mass Kg (Lbs)	Mass @DOF Kg (Lbs)	% Mass @ DOF	Excess Mass Kg (Lbs)
Pseudo-Prototype ($1/10^{th}$)	L_p/L_r	M_p/Lr^2	62.8 (138.5)	21.4 (47.2)	34	--
1/3 ($1/13^{th}$)			35.5 (78.3)	12.1 (26.7)	34	11.4[(1)] (24.9)
(1/2) ($1/20^{th}$)			15.7 (34.6)	5.4 (11.9)	34	4.9 (10.8)

[(1)]Excess mass = 35.5-2*12.1=11.4 kg (24.9 lbs)

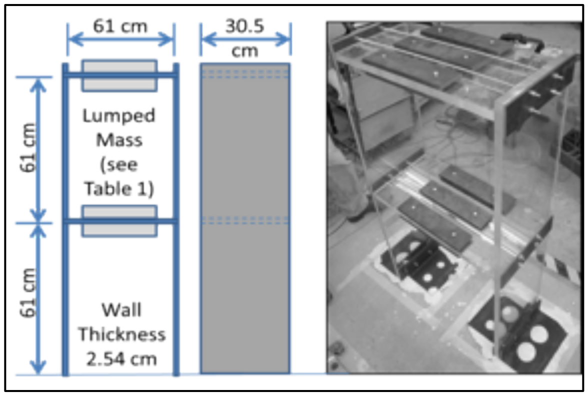

Figure 2. Sample dimensions of pseudo-prototype ($1/10^{th}$ scale physical model)

4. FREE VIBRATION TESTING OF PHYSICAL MODELS

Free vibration testing of the physical models was performed in order to experimentally validate the dynamic similitude based design and construction. The testing was conducted using a light impact hammer to induce free vibrations and the response was obtained using capacitance type accelerometers located at the two degrees of freedom. The impact hammer tests were conducted with the physical models anchored to the concrete floor via the use of hydrocal to create a fixed base as well as with the models bolted to the shake table. The two boundary conditions (ground floor and shake table) were used to establish any differences arising from shake table-model interaction effects.

The free vibration time history responses were used to create the Frequency Response Function (FRF). Comparison of the (FRF's) with the physical models anchored to the ground floor and bolted to the stationary shake table is shown in Figure 3. As shown, *the shake table tends to amplify the difference between the responses and this effect is aggravated with model height*. This amplification in the response is most likely due shake table kinematics that tends to modify and amplify the response when compared to a "fixed" boundary condition. As a result, the free-vibration tests conducted on the ground floor were viewed as being closer to reality.

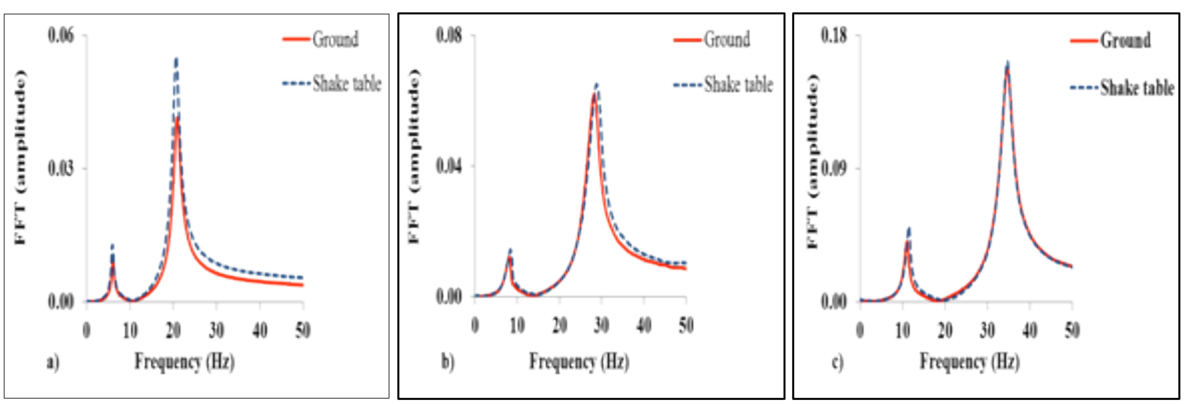

Figure 3. FRF of physical models a) Pseudo-prototype b) 1/3 and c) 1/2 physical scales

A comparison of the "scaled-up" frequency response function (FRF's) between the three physical models was prepared to experimentally validate dynamic similitude requirements used in the design and construction of the physical models. The "scaled-up" frf's were obtained by dividing the unscaled frequencies by the square root of the scaled factor ($\sqrt{L_r}$) and the "scaled-up" amplitude with units of acceleration over force (a/f) was determined by dividing the force by L_r^2 (Fig. 4). The natural frequencies of each model were below the 50Hz operating range of the shake table.

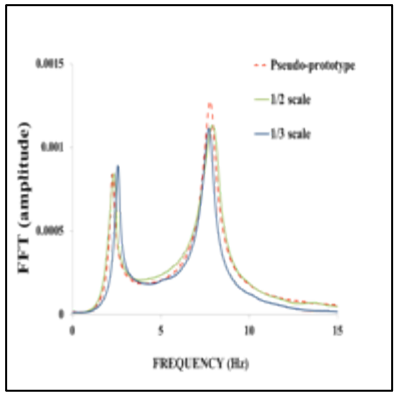

Figure 4. "Scaled-up" FRF responses for all physical models with the base "anchored" to ground floor

4.1. Shake table tuning

The shake table used in this research was a uni-axial model R-136 manufactured by ANCO Engineers (Boulder, Colorado). The tabletop is constructed of steel with a plan dimension of 53 in. by 42 in. and a weight of 1500 lbs. The table has a 10-kip actuator controlled by a two-stage servo-valve capable of replicating accelerations up to 4.0g. The system has a maximum displacement of +/- 2.8 in., an operating frequency range up to 50 Hz, and an overturning moment capacity of 7,500 ft-lbs. The shake table was tuned using the heaviest model based on best practices recommended by the manufacturer.

4.2. Shake table simulations

Upon validation of the physical models and tuning of the shake table, dynamic testing on the shake table with the elastic models fixed to the shake table was conducted by using the El Centro earthquake as well as the square-wave time history used for tuning of the shake table. To understand the potential effect of the physical models on the response of the shake table simulations were conducted including a) bare shake table, b) with the physical model located on the shake table. These simulations were conducted for each physical scale.

The shake table time history responses obtained by processing the input at each scale was then used to assess the inelastic response thru analytical simulations using finite element non-linear models. Several parameters were evaluated to establish the inelastic response across story heights and physical scales.

4.3. Comparison of acceleration time histories

The acceleration time histories used for this study included the El Centro earthquake record of May 19, 1940 North-South Component (due to the large amount of research which employs this particular record) and a low-amplitude and low frequency square wave (since this is considered a very stringent input and is commonly used for tuning shake tables). Prior to implementing the time histories, the time step was scaled to the appropriate level for each model using the laws of similitude. To control the shake table, the scaled acceleration time histories in digital format were then converted to an equivalent analog time history using the Data Physics 550 vibration controller. The analog conversion was obtained by sampling the input data at the same frequency to prevent data aliasing during the conversion process.

A comparison of the desired (input) and feedback (output) El Centro time histories for the three different scales are shown (Figure 5) for the 1/10, 1/13 and 1/20 scales, respectively. Given the small mass of the physical models, this series of tests could be considered a best-case scenario. Even for the largest model, the total mass was less than 10% of the table's payload capacity and thus model/table interaction is negligible (this was confirmed by running the time histories with and without the models on the table).

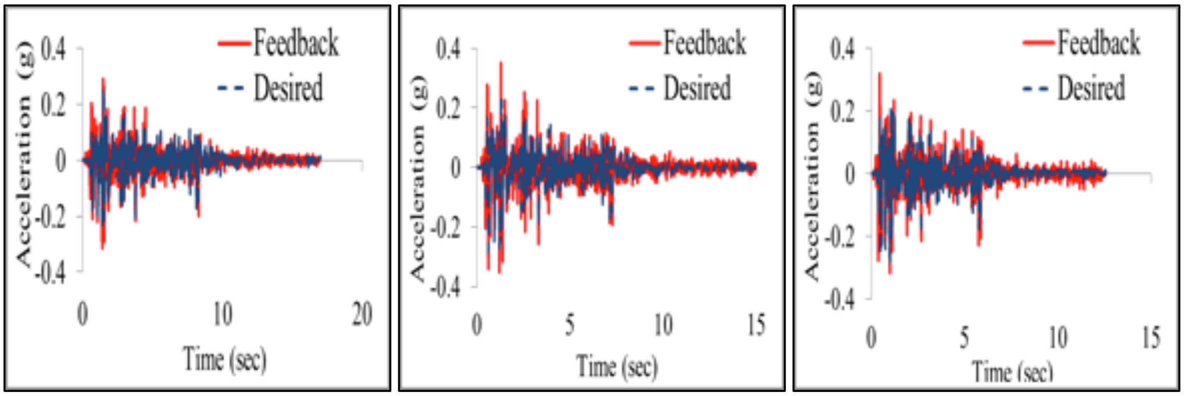

Figure 5. Shake table time-domain response for El Centro "feedback" versus "desired" time histories at 1/10, 1/13 and 1/20th physical scale (left to right).

To offer a comparison of the error between the feedback and desired signals, the Root Mean Square (RMS) Error was used to determine the cumulative error in the reproduction of the input signal. This error was computed as reported by Conte et. al. (2010). The largest RMS error between the feedback and desired signal for the 1/10th, 1/13th and 1/20th physical scales was found to be 52.68%, 54.32% and 64.60% respectively (Figure 6).

As a result, it is noted that the observed differences are not unique to the specific shake table employed within this study, but are perhaps indicative of servo hydraulic shake tables.

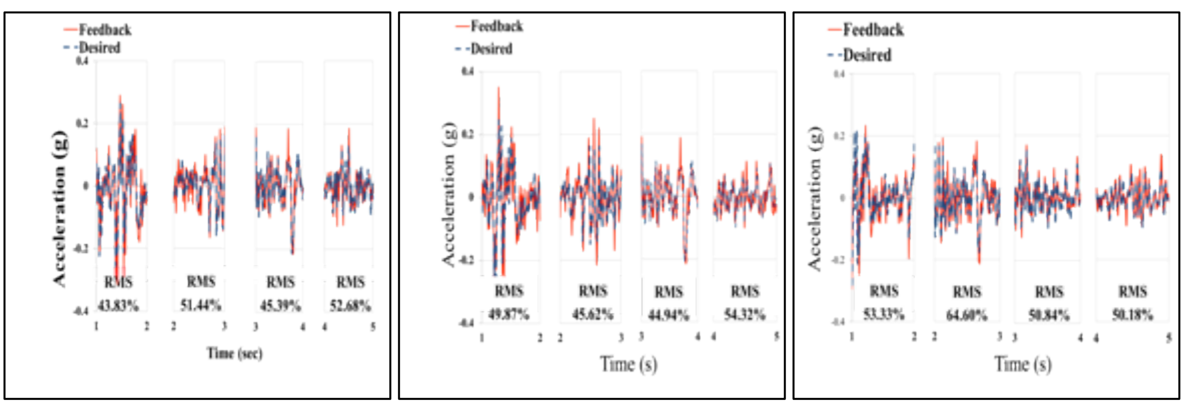

Figure 6. RMS Error for El Centro "feedback" versus "desired" time histories at 1/2 physical scale.

5. NONLINEAR ANALYTICAL SIMULATIONS

To examine the influence the discrepancies between the feedback and the desired time histories have on the inelastic response of structures, an analytical parametric study was designed and executed. The primary variables examined throughout the analytical study included a structures frequency band (through the variation of number of stories), scaling factor, and level of nonlinearity (through demand-to-capacity ratios).

To examine the influence of acceleration tracking performance, each of the models were employed in two non-linear time-history analyses; one using the desired earthquake record and one using the feedback earthquake record. Since the size of the models employed within the experimental portion of the study did not influence the acceleration tracking performance of the shake-table, using the feedback records obtained within the parametric study will lead to a 'best case' scenario as the larger models (e.g. six story models) may have had a negative influence on the performance of the shake-table experimentally.

The models were developed within the Strand7 finite element software package and employed nonlinear plane frame elements for the columns and rigid floors with lumped mass to ensure similitude with the experimental models (for the two-story case). The nonlinear frame elements were equipped with an elastic-perfectly plastic nonlinearity model and they had the capability to form hinges at any point along the length of the element. The analytical models consisted of "thin-beam" elements in Strand7 with six degrees of freedom at each node. These types of elements follow classic beam bending theory and assume plane sections remain plane and plane sections remain normal to the tangent of the deflection curve. Also, an analysis was conducted to determine the required element discretization to ensure non-linear response was fully captured.

6. RESULTS

To allow a comparison of the overall response of the various analytical models, the total amount of energy dissipated during the earthquake record was selected as the primary metric. This was calculated by integrating the force-displacements responses of each story for the entire time-history using the trapezoidal rule. The global amount of energy dissipated for each model was then computed as the summation of the energy dissipated by each story. The total energy dissipated throughout the time-history analysis for each model was then plotted against the C/D ratio for each scale and story height (Figures 7 through 9).

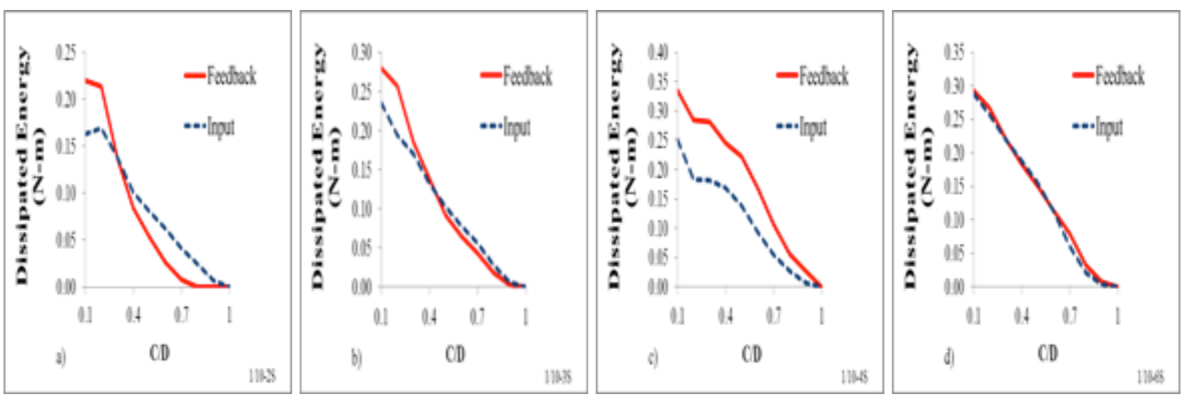

Figure 7. Energy dissipation across story heights – 1/10th Scale Model (El Centro)
(a) 2 story "base" model (b) 3 story (c) 4 story and (d) 6 story models

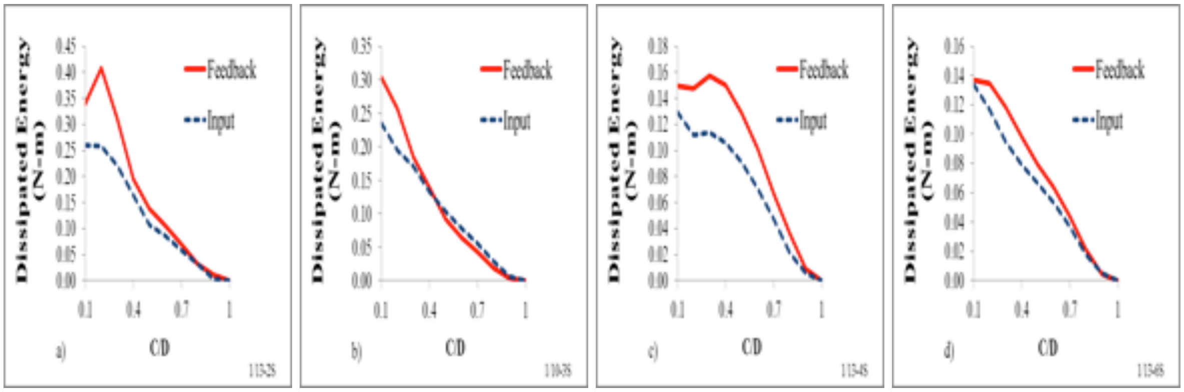

Figure 8. Energy dissipation across story heights – 1/13th Scale Model (El Centro)
(a) 2 story "base" model (b) 3 story (c) 4 story and (d) 6 story models

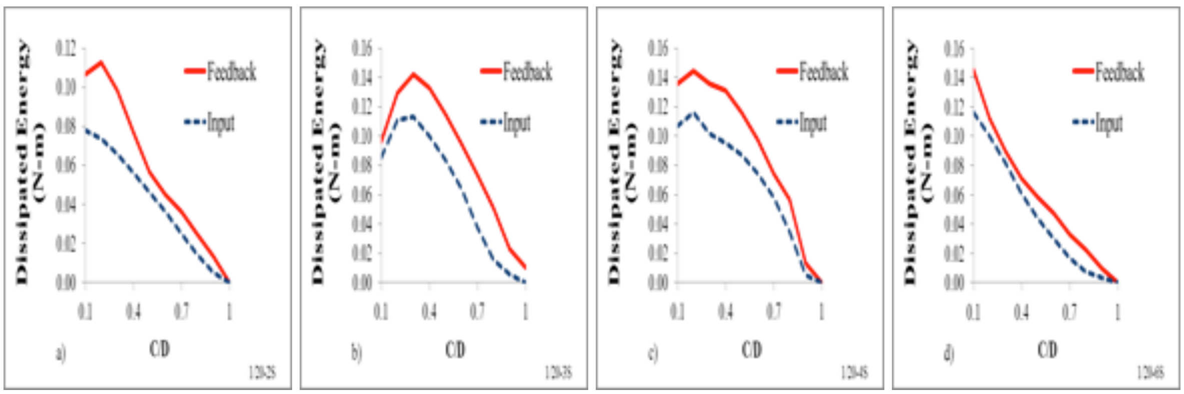

Figure 9. Energy dissipation across story heights – 1/20th Scale Model (El Centro)
(a) 2 story "base" model (b) 3 story (c) 4 story and (d) 6 story models

7. DISCUSSION

The energy dissipation trends observed across story heights for the two-story model for the El Centro time histories shows that the dissipated energy for the desired earthquake is not the same as for the feedback earthquake. For the 1/10th physical scale, the desired and feedback energy dissipation trends crossed at a C/D ratio of 0.3. That is, at C/D ratios less than 0.3, the feedback earthquake caused the model to dissipate more energy while at C/D ratios larger than 0.3 (i.e., as the structure becomes less non-linear), the desired earthquake caused the model to dissipate more energy.

This observation indicates that the differences between the responses induced by the feedback and desired earthquake are not constant and in fact vary with the level of nonlinearity present. This is important as many shake table studies employ a single record and scale its amplitude to drive the structure to increasing levels of nonlinearity, and as such observe trends that may not be consistent with the desired earthquake they have selected for the study.

Moreover, the 1/10th scale three-story model also shows this "flip" between the desired and the feedback earthquakes at a C/D ratio of 0.4. For the four story and six story 1/10th scale models, (Figure 7c and 7d) the "flip" was not observed. In addition, the energy dissipation trends for the 1/10th scale six-story model (Figure 7d) were essentially identical for the both the desired and feedback earthquakes. This is likely due to the fact that as the structure becomes taller, the natural frequencies associated with modes with large mass participation drop (longer building periods). Since it is easier for the shake table to replicate lower frequency content, the discrepancies between the desired and feedback earthquakes diminishes as the first few frequencies of the models decrease.

For the 1/13th physical scale, the response associated with the feedback is almost always larger than the response given by the desired signal, across all story heights. A plausible explanation could be related to the fact that as the physical scale becomes smaller with an increase in the frequency content; the shake table is less able to produce a feedback that approximates the desired signal. The same trend holds true for the 1/20th physical scale, where the feedback always results in larger energy dissipation across all story heights examined.

8. CONCLUSIONS

Based on the results of this research, the following conclusions can be drawn:

1. Free-vibration tests of the physical models conducted on a stationary shake-table and on ground floor indicate that the shake table amplifies the difference in response and it is exacerbated with model height. This effect resulting from shake table kinematics introduces undesired “artificial” rotations that predominantly impact higher frequency content in the model.
2. Shake-tables can both 'amplify' and 'attenuate' the desired inputs (depending on their specific character) and either of these modifications can increase or decrease responses - depending on the level of nonlinearity and the frequency band of the model/table.
3. Acceleration tracking performance of shake tables can play a key role in the uncertainty associated with the nonlinear response, however; this uncertainty can be minimized with model/table low frequency bands in the (1-3 Hz) range.
4. Shake table acceleration tracking performance impacts dynamic similitude and the uncertainty is exacerbated at very small physical scales primarily due to time scaling effects.
5. Testing on a small shake table can offer insight on trends and behavior mechanisms; however, the uncertainty associated with the shake table response can vary between 40 to 60% between the feedback and the desired input. As a result, one should never expect to be able to learn something from shake table tests in an absolute sense.

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