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DEVELOPMENT AND EXPERIMENTAL VALIDATION OF A 3-D SEISMIC ISOLATION SYSTEM USING LS-DYNA

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Abstract

A novel three-dimensional (3-D) seismic isolation system is proposed for the new Loma Linda University Medical Center replacement hospital to protect the building from the predicted severe near-fault earthquake shaking at the site. This paper presents detailed development and experimental validation of the analytical components in LS-DYNA that are used in this first-of-its-kind vertical isolation system (VIS). The VIS comprises an assembly of helical coil springs, fluid viscous dampers, and low-friction sliding shear pins mounted to a suspended concrete filled steel pedestal. Each of these pedestals in turn supports one of the 126 triple friction pendulum bearings used to provide lateral seismic isolation. The LS-DYNA modeling approach used here was validated against an existing full-scale shake table test of a 3-D isolated electrical transformer conducted at the University at Buffalo. Good agreement between analysis and experimental results was achieved and the LS-DYNA model accurately captured both the local and global response of the components, subassemblies, and overall building to 3-D ground motion inputs. Series of full scale prototype testing are required for each VIS components to calibrate properties used in the analytical and to validate the entire proposed subassembly, a testing program is proposed at the SRMD facility at UC San Diego.

Keywords: 3-D seismic isolation; experimental validation; LS-DYNA; full-scale testing

1. Introduction

The replacement hospital for Loma Linda University Medical Center (LLUMC) is a new 1,000,000 square foot Adult and Pediatric Trauma Center serving the Inland Empire in Southern California. This 17-story essential facility is located less than 1 km from the M7.9 capable San Jacinto fault zone and the site specific seismic hazard predicts the generation of MCE spectral accelerations of $S_{M1,horizontal}$ = 2.31g and $S_{MS,vertical}$ = 2.92g. The design ground motions developed for the project include near fault pulse-like horizontal ground motion and severe vertical ground motion.

A wide variety of structural steel lateral system configurations were considered before concluding that the optimal structural system was a combination of base isolation with BRB’s and SidePlate moment frames above. The horizontal base isolation system comprises 126 triple friction pendulum (TFP) bearings with +/-42” displacement capacity manufactured by Earthquake Protection Systems and 104 fluid viscous dampers with 800 kip MCE capacity manufactured by Taylor Devices. The pendulum isolators have an effective period of 4.5 seconds and the dampers have a velocity exponent of 0.7. The total equivalent system damping coefficient is 50% of critical damping.

A novel 3-D isolation system was developed to reduce the impact on the structure and protect the critical contents due to the high site-specific vertical ground motion component [1]. The 3-D isolation system couples a traditional lateral isolation system of triple friction pendulum isolators and large stroke fluid viscous dampers with a novel vertical isolation system (VIS) of steel pedestals, helical coil springs, fluid viscous dampers, and low friction sliding shear pins. In the past, there have only been a few known cases where isolation systems were able to provide isolation of the vertical seismic component and mitigate the vertical seismic amplification of a structure. Due to construction schedule constraints and to ensure compliance with the California SB 1953/SB 90 deadline for occupancy, the vertical component of the 3D seismic isolation system was configured to be installed after construction of the main structural frame.

The original seismic design and analysis of the structure used LS-DYNA to efficiently perform nonlinear response history analysis (NLRHA) with 110 individual ground motion analyses incorporating DE, MCE, upper bound and lower bound properties, and varying ground motion direction [2]. The conception and design of the VIS and the NLRHA in LS-DYNA were both done by Arup. In the following sections, the numerical modeling approach for the VIS assembly in LS-DYNA is discussed and validated using existing shake table test results.

2. Modeling of Vertical Isolation System Components

The Vertical Isolation System (VIS) comprises an assembly of helical coil springs, fluid viscous dampers, and low-friction sliding shear pins mounted to a suspended concrete-filled steel pedestal (Fig. 1). Each of these pedestals supports one of the 126 TFP bearings used to provide horizontal seismic isolation. The VIS was modeled in LS-DYNA using spring, damper, and seismic isolator type materials as described in the following sections and shown in Fig. 2.

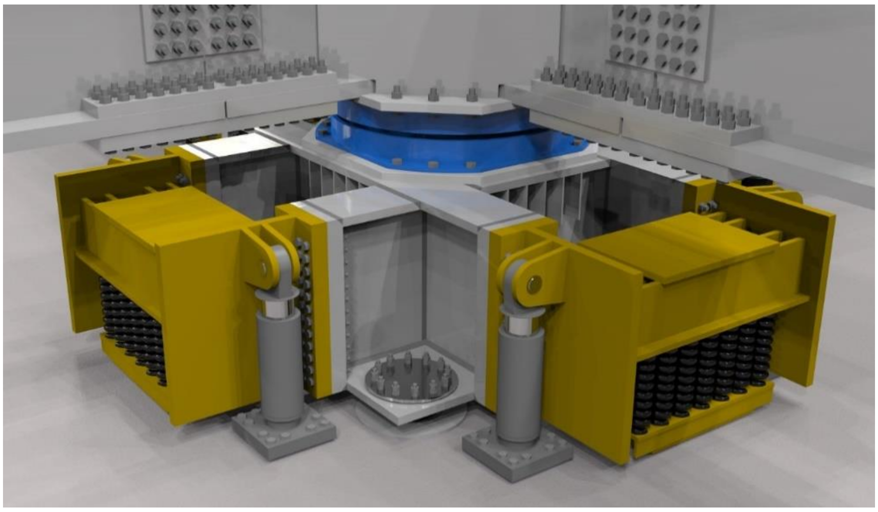


Fig. 1 – Rendering of VIS with helical spring boxes, dampers, and sliding shear pins mounted to concrete-filled steel pedestal and sitting below Triple Friction Pendulum (TFP) bearings

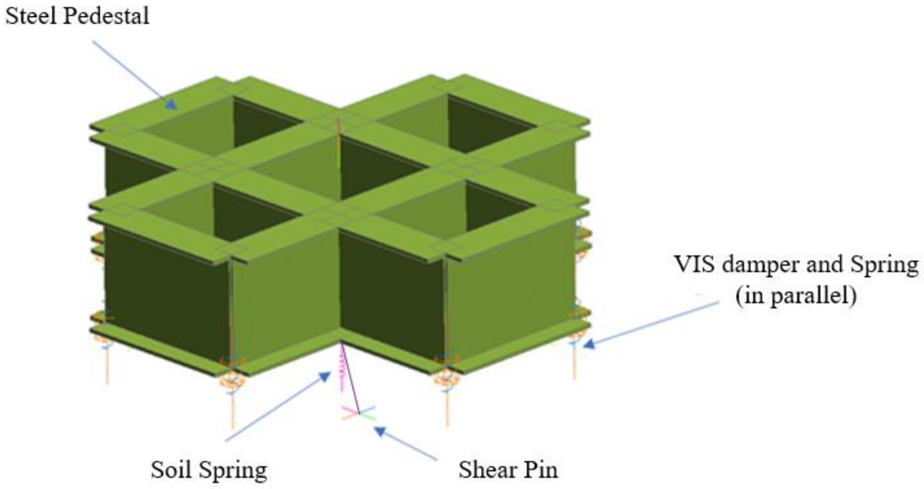


Fig. 2 – VIS as modeled in LS-DYNA

2.1 Dampers

Each VIS assembly has a set of linear dampers (Fig. 1) and these dampers were modelled in LS-DYNA using the MAT_S02 (Damper_Viscous) material.

2.2 Springs

Each VIS assembly has a set of springs (Fig. 1) with a unique force-displacement curve due to its sprung weight. These springs were modelled in LS-DYNA using the MAT_S04 (Spring_Nonlinear_Elastic) material. Fig. 3 shows a sample theoretical force-displacement curve for one of these springs normalized by sprung weight. These were defined to reduce rocking effects and with zero tensile capacity.

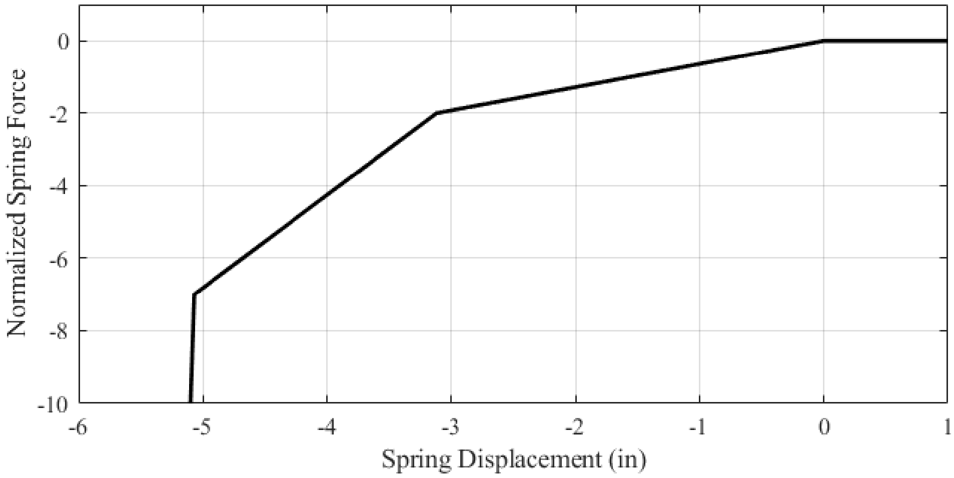


Fig. 3 – Normalized spring force-displacement curve (compression is negative, tension is positive)

2.3 Shear Pins

Each VIS assembly has a set of sliding shear pins (Fig. 1) that constrain the pedestal assembly and mat foundation in the horizontal direction while allowing the base of the pedestal to move vertically relative to the mat foundation. Five different diameters for shear pins were considered, and for each type, the diameter of the sliding shear pin dictates its horizontal stiffness. In the vertical direction, the sliding shear pins provide friction forces depending on the contact pressure and coefficient of friction between the two surfaces. Each sliding shear pin was modeled using four MAT_SEISMIC_ISOLATOR beam elements oriented horizontally in a cruciform, with an elastic beam element to represent the plate connecting the shear pin (at the center of the cruciform) to the pedestal. Properties of these equivalent beams were calculated using elastic plate theory (considering two adjacent free edges and two adjacent clamped edges) to capture the effects of each plate's flexibility [3]. The seismic isolator elements provide the low friction sliding behavior in the vertical direction and the specified resistance in the horizontal direction. For the validation analysis, the prescribed displacements were applied at the free end of the steel plate beam (where it connects to the pedestal), while the free (outer) ends of the seismic isolator elements were fixed against translation (Fig. 4).

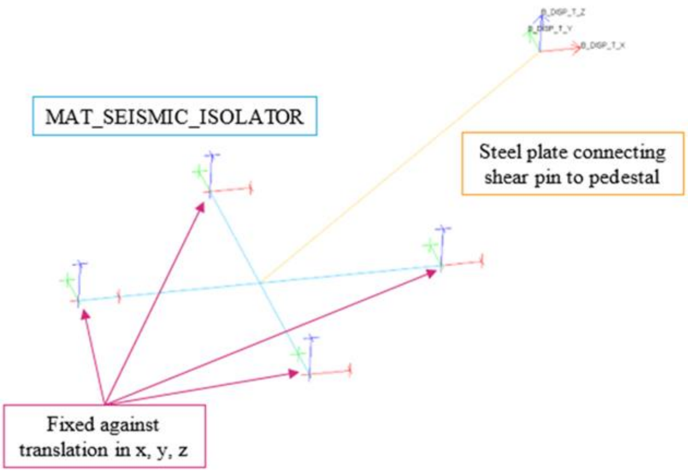


Fig. 4 – Sliding shear pin configuration

Horizontal and vertical behavior of the five different diameters of the shear pins were validated against their theoretical force-displacement behavior for varying levels of prescribed horizontal and vertical displacement. The resulting displacement time histories, force time histories, and force-displacement behavior in both horizontal and vertical directions are shown in Fig. 5. As can be seen from the results, the horizontal displacements deviate from the prescribed displacements due to the stiffness of the steel plate beam, the angle at which it connects to the shear pin, and the interaction of the four MAT_SEISMIC_ISOLATOR elements simultaneously resisting through both friction and varying levels of contact stiffness. The vertical displacement results almost exactly match the prescribed displacement as the steel plate beam is free to slide up and down due to the limited resistance from friction. The horizontal and vertical force results vary between the five types due to the difference in pin diameters which leads to a difference in horizontal stiffness for each shear pin. This can also be seen in the horizontal hysteresis curves where the slope of each shear pin's stiffness curve closely matches the associated stiffness value. The vertical hysteresis curves are a close match to the modeled friction parameters of both the upper and lower bound models. Overall there is a very good match between the theoretical and modeled LS-DYNA behavior. Once experimental results are available, the LS-DYNA model will be validated against these as well.

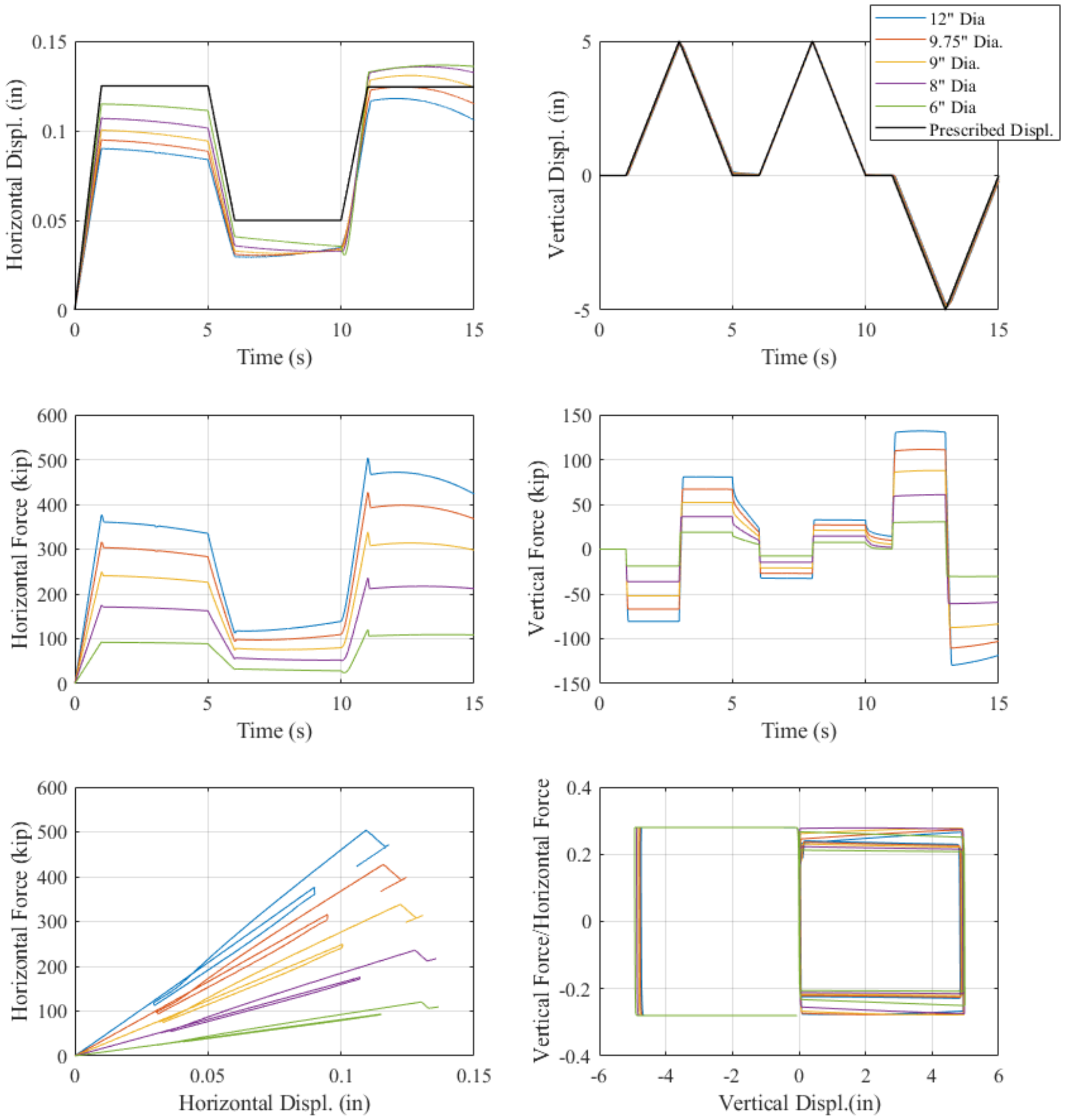


Fig. 5 – Horizontal and vertical response of different sliding shear pins

3. Validation of VIS Assembly Modeling Procedure

A validation study using an existing shake table test was required to ensure that the proposed modeling procedure of the VIS system in LS-DYNA could accurately capture both local and global responses of the structure under 3D shaking. For this validation study, a shake table test conducted on a transformer superstructure assembly (Fig. 6 (a)) at the University of Buffalo was used [[4], [5]]. The aim of this experimental study was to test the effectiveness of a three-dimensional seismic isolation system using reliable, passive, and readily available devices from reputable manufacturers. The isolation system consisted of horizontal isolators and vertical spring-damper units. A steel frame was the main superstructure system, and a steel plate and bushing were bolted on top. Additional plates around the steel frame were added to achieve the desired specimen weight. Several configurations of the models were designed and tested. For the validation study discussed in this paper, the free-rocking configuration was used as it was most similar to the VIS system for LLUMC.

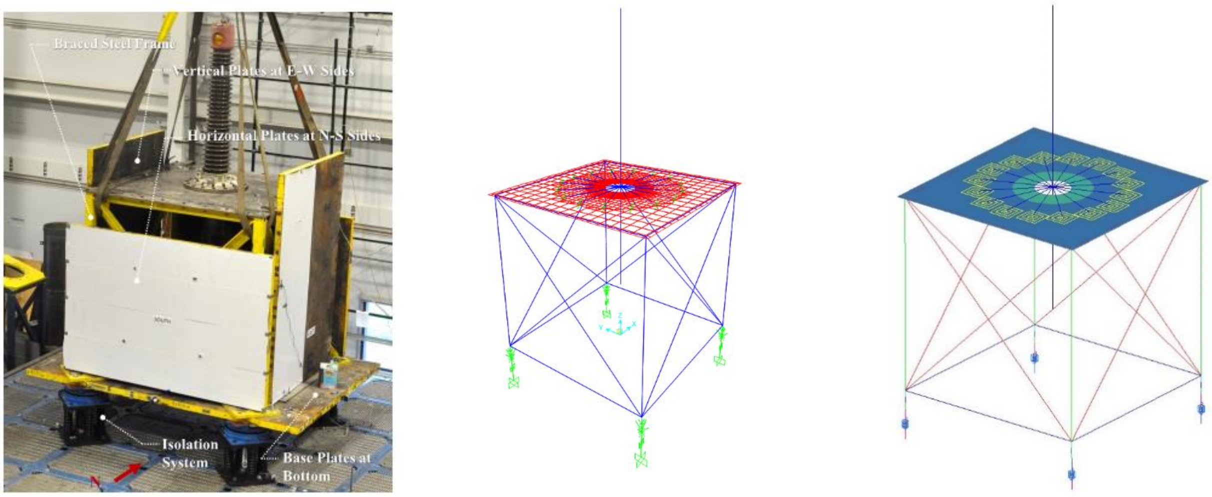
The seismic isolation system consisted of four TFP isolators and four vertical spring-damper units at each corner. Each VIS assembly had a configuration similar to those used for LLUMC. The properties of the isolators, springs, and damper units were tested and summarized in Table 1. More details can be found in the MCEER 17-0007 report [[5]].

Table 1 – Properties of the TFP isolators, springs, and damper units

<table>
<tr><td rowspan="3">Triple Friction Pendulum</td><td>Sliding Surface</td><td>f_min</td><td>f_max</td><td>Rate parameter [sec/in]</td><td>Effective radius [in]</td></tr>
<tr><td>Inner slider</td><td>0.015</td><td>0.02</td><td>0.7</td><td>3.5</td></tr>
<tr><td>Outer slider</td><td>0.09</td><td>0.13</td><td>0.7</td><td>35.5</td></tr>
<tr><td rowspan="2">Spring</td><td colspan="3">Axial stiffness [kips/in]</td><td rowspan="2">Damper</td><td>Damping constant [kips-sec/in]</td></tr>
<tr><td colspan="3">6.44</td><td>0.53</td></tr>
</table>

3.1 Numerical model

In this study, a SAP2000 analytical model of the test specimen was created for additional investigation and was used as a reference to create the LS-DYNA model. Both SAP2000 and LS-DYNA models are shown below in Fig. 6. The key modeling assumptions used in LS-DYNA are discussed below.



(a) (b) (c)

Fig. 6 – 3D Base Isolated High Voltage Transformer: Specimen at University at Buffalo (a) Experimental set up (b) SAP2000 Analysis model (c) LS-DYNA Analysis model

3.1.1 Superstructure model

The analysis model of the superstructure was created in LS-DYNA based on the data provided in the MCEER 17-0007 report with similar modeling assumptions and properties in the SAP2000 model including: element types (beam and shell elements), material properties (density and young's modulus), lumped masses, and nodal constraints. For the rigid material used in SAP2000 to model the cover plate, bushing, and base connecting beams, a large stiffness modifier was assigned to the Young's modulus in LS-DYNA. The effects of this change on the behavior of the model was found to be negligible through a sensitivity check.

3.1.2 Horizonal isolation system model

The modeling of the TFP bearing in LS-DYNA used three beam elements in series with a seismic isolator material (MAT_SEISMIC_ISOLATOR). The equivalent pendulum length for each beam element was calculated based on the provided radius summarized in Table 1. For the beam elements representing the outer two sliding surfaces, an effective pendulum length of 32 inches was used. For the beam representing the inner sliding surface, an effective pendulum length of 7 inches was used. This conversion from the actual radii to the material properties was performed based on the theory proposed by Fenz and Constantinou for the modeling of TFP isolators using a series model [[6]].

The corresponding minimum and maximum friction coefficients were input to the associated beam element material representing the specific pendulum system. Using reported input parameters for effective radius and friction properties, the LS-DYNA model produced a similar horizontal hysteresis for the TFP isolator compared to the SAP2000 model. Fig. 7 presents a comparison of horizontal normalized hysteresis of the TFP isolators in SAP2000 and LS-DYNA.

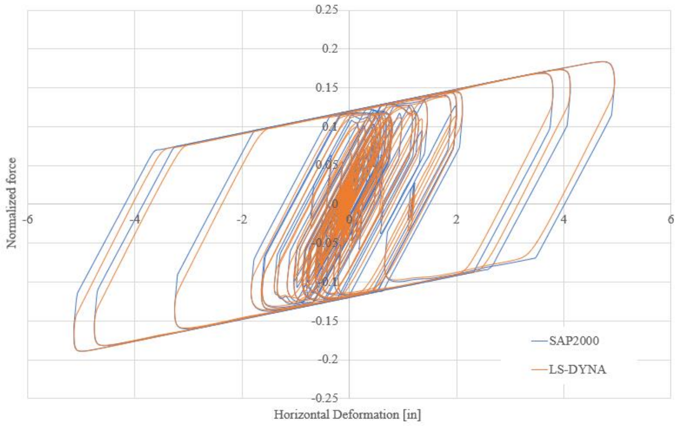


Fig. 7 – Comparison of Isolator hysteresis in SAP2000 and LS-DYNA

3.1.3 Vertical isolation system

For the vertical spring and damper units, MAT_S01 (SPRING_ELASTIC) and MAT_S02 (DAMPER_VISCOUS) were used, respectively.

3.2 Modal analysis result

A modal analysis was performed to compare the dynamic properties of the LS-DYNA model with reported values from the modal analysis using SAP2000 to preliminarily assess the validity of the numerical model. Based on the analysis results summarized in Table 2, the modal behavior of the two analysis models were nearly identical.

Table 2 – Modal analysis results comparison

Mode	Mode Description	Frequency [Hz]	
		SAP2000	**LS-DYNA**
1	Global translation X	0.367	0.367
2	Global translation Y	0.37	0.367
3	Global torsion	0.382	0.381
4	Global rocking X	1.436	1.432
5	Global rocking Y	1.436	1.432
6	Global translation Z	1.914	1.916
7	Bushing rocking X	11.038	11.019
8	Bushing rocking Y	11.038	11.019
9	Bushing translation Z	13.34	13.317

3.1.8 Validation results

The validation analysis results from LS-DYNA were compared with the experimental results and the analytical results from SAP2000. At the top of the superstructure frame, the acceleration response history and the acceleration spectrum for both horizontal and vertical directions were compared. In addition, the horizontal isolator displacement history, orbit, and vertical spring and damper deformations were compared. Results from the El Centro 250% record are shown below (Fig. 9 and Fig. 8). Based on the provided comparison results, the LS-DYNA model is able to capture the true local and global behavior of the structure and match the experimental results. The LS-DYNA results are very similar to the SAP2000 results, and in some cases predict the experimental results slightly better, particularly for isolator horizontal displacements and spring vertical deformations. It can be concluded that the modeling techniques used for the VIS system in LS-DYNA can accurately capture the responses observed in the shake table test under tri-axial ground motion loading conditions. The rocking behavior can also be captured as reflected by the matching of the individual damper and spring vertical deformations at each corner.

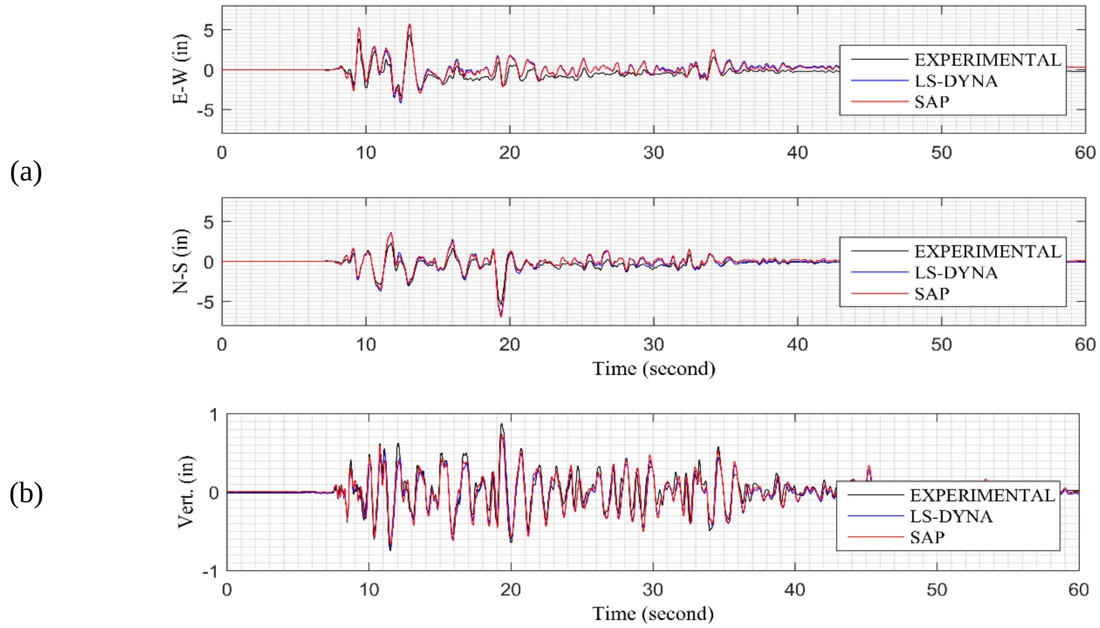


Fig. 8 – Comparison of experimental and analytical results for Configuration of Free Rocking in El Centro 250% Motion. (a) Displacement histories of friction pendulum at SW corner, (b) Vertical displacement of spring-damper unit at NE corner

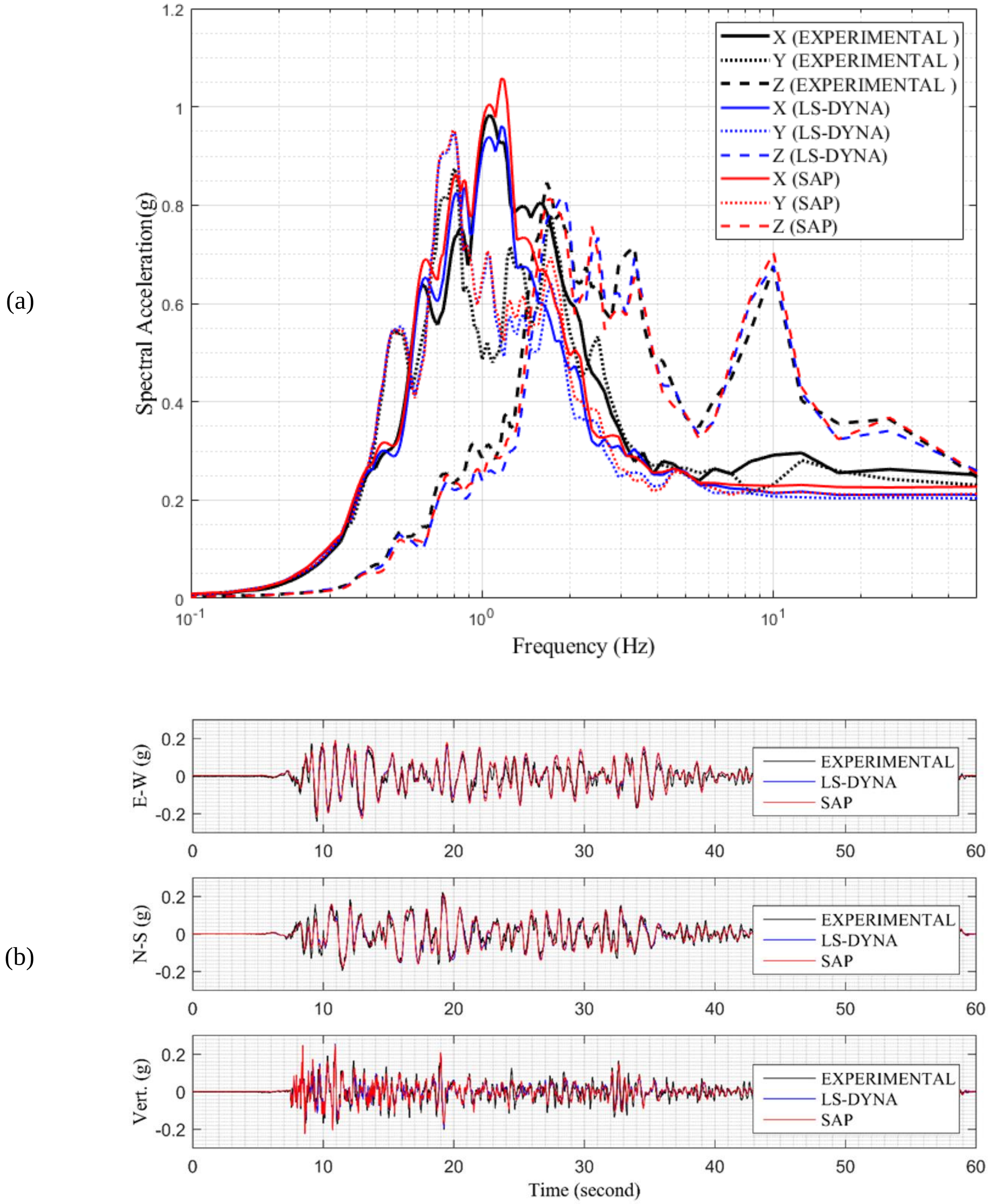


Fig. 9 – Comparison of experimental and analytical results for Configuration of Free Rocking in El Centro 250% Motion. (a) 5%-damped response spectra at Frame NE Top Corner, (b) Acceleration histories at Frame NE Top Corner

3.1.7 Sensitivity study on modeling of spring assembly

For the actual test specimen, there were four coil springs in one assembly as shown in Fig. 10. One spring element was used in the LS-DYNA model to represent the whole spring assembly and the rotation on top of the spring was fixed. However, from the experimental video, it was observed that a slight rotation might happen at the bottom of the isolator concave due to the different vertical deformations of the four coil springs. Therefore, an analysis model with all four springs explicitly modeled was investigated. The purpose was to investigate if this could result in a better match against the experimental results. Three different modeling configurations were analyzed as shown in Fig. 11. Response history analysis results of each configuration were compared with the original configuration with only one spring element. Slight discrepancies of the deformation of the 4 springs at the same corner location were observed. However, the overall responses were almost identical. For this validation study, the one spring model similar to the SAP2000 model was used.

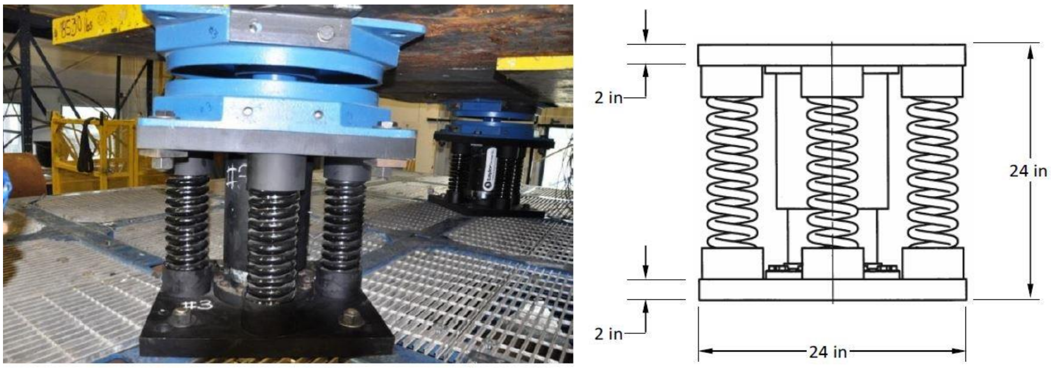
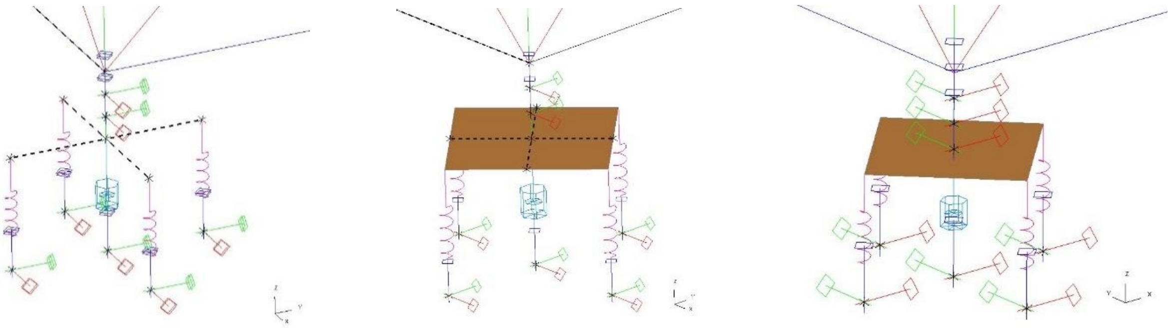


Fig. 10 – Assembly of the coil spring unit [[5]]



(a) (b) (c)

Fig. 11 – Configurations considered in the sensitivity study when all four spring units were modeled

4. Experimental Tests

Prior to construction, full scale prototype and production testing is required to establish and validate the design properties of different components of the VIS (vertical fluid viscous damper, sliding shear pins, and helical springs) used in the analysis and design. Currently, full-scale testing and validation of the VIS components and assemblies is in progress. Once available, the LS-DYNA model and element properties will be calibrated based on the experimental results.

In addition, a full scale testing program of a VIS pedestal assembly, including TFP isolator, sliding shear pins, vertical dampers, and helical springs has been proposed at the SRMD facility at UC San Diego. This testing program incorporates different characterization tests as well as prescribed displacement demands from different 3-D earthquake excitations to ensure that the response of the full scale assembly is as expected.

5. Conclusions

This paper presented detailed development and experimental validation of the analytical components in LS-DYNA that were used in this first-of-its-kind vertical isolation system (VIS). The modeling methodology for each component was described and validated against an existing full-scale experimental test. It was shown that the proposed modeling approach can accurately capture both the local and global response of the different components, subassemblies, and overall building to 3-D ground motion inputs. Future full scale assembly experimental testing will be undertaken to further validate the behavior of the VIS as a whole.

6. Acknowledgements

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7. Copyrights

8. References

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