16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1075

Registration Code: S-Q1464740698

PRESERVING A NATIONAL TREASURE: SEISMIC ISOLATION OF SPACE SHUTTLE ENDEAVOUR

D. R. Jenkins(1), A. Zekioglu(2), H. Darama(3), H. Freudenberger(4) and A. Nulman(5)

(1) *Project Director, California Science Center, djenkins@cscmail.org*
(2) *Arup Fellow, Arup-Los Angeles, atila.zekioglu@arup.com*
(3) *Associate, Arup-Los Angeles, huseyin.darama@arup.com*
(4) *Senior Engineer, Arup-Los Angeles, hani.freudenberger@arup.com*
(5) *Associate Principle, Arup-Los Angeles, amie.nulman@arup.com*

Abstract

This paper describes performance based seismic design of the support structure for the Space Shuttle *Endeavour* in launch-ready position that will be exhibited in the new California Science Center Samuel Oschin Air and Space Center building. The project is in the final construction document phase. Zimmer Gunsul Frasca Architects LLP (ZGF) are the project architects. Arup North America Limited (Arup) are the multidisciplinary engineering consultants, including structural engineering.

This national treasure is preserved by utilizing seismic isolation concept with friction pendulum isolators. The design relies on six friction-pendulum seismic isolators to break the horizontal connection between the orbiter and the ground in the event of an earthquake. The seismic isolators enable *Endeavour* to glide gently back and forth on low-friction sliders, thus protecting the shuttle support structure and the shuttle itself from the direct impact of an earthquake.

The Space Shuttle Exhibit (Stack) is comprised of the Orbiter *Endeavour* (ORB), an External Tank (ET), two Solid Rocket Boosters (SRBs), and connection hardware/elements (CHE) that the Science Center has acquired from various sources. All of the artifacts are real flight hardware originally designed for use in the NASA space shuttle program. The ORB is attached to the ET and is cantilevered nearly 25 feet from the center of SRB supports. The Stack is connected to the isolated concrete pad at the same 8 hold-down anchor locations in the SRBs, 4 at each SRB, used during actual launches. Due to the large eccentricity of the Orbiter's center of gravity with respect to the centroid of the SRB to concrete pad connection, the Stack experiences permanent overturning at the base of the SRBs, which amplifies with the seismic loads. This level of overturning creates significant axial tension in the SRB hold downs. Due to eccentricity of the Orbiter, vertical seismic motion is an important factor for the performance of the Stack. This paper aims to describe the approach to the design of the supporting structure and the performance evaluation of the Stack members under seismic loads.

Keywords: Shuttle Launch Stack Exhibit, Seismic Isolation, Friction Pendulum, Nonlinear Response History Analysis, LS-Dyna

1. Introduction

This paper describes performance based seismic design of the support structure for the Shuttle Stack in launch-ready position that will be exhibited in the new California Science Center Samuel Oschin Air and Space Center building. This national treasure is preserved by utilizing seismic isolation concept with friction pendulum isolators. The design relies on six friction-pendulum seismic isolators to break the horizontal connection between the orbiter and the ground in the event of an earthquake. The seismic isolators enable *Endeavour* to glide gently back and forth on low-friction sliders, thus protecting the shuttle support structure and the shuttle itself from the direct impact of an earthquake.

The Space Shuttle Exhibit (Stack) is comprised of the Orbiter *Endeavour* (ORB), an External Tank (ET), two Solid Rocket Boosters (SRBs), and connection hardware/elements (CHE) that the Science Center has acquired from various sources. All of the artifacts are real flight hardware originally designed for use in the NASA space shuttle program. The ORB is attached to the ET and is cantilevered nearly 25 feet from the centre of SRB supports. The Stack is connected to the isolated concrete pad at the same 8 hold-down anchor locations in the SRBs, 4 at each SRB, used during actual launches. Due to the large eccentricity of the Orbiter's center of gravity with respect to the centroid of the SRB to concrete pad connection, the Stack experiences permanent overturning at the base of the SRBs, which amplifies with the seismic loads. This level of overturning creates significant axial tension in the SRB hold downs. Due to eccentricity of the Orbiter, vertical seismic motion is an important factor for the performance of the Stack. This paper aims to describe the approach to the design of the supporting structure and the performance evaluation of the Stack members under seismic loads. See Figure 1 for visual of Stack and support system.

The isolators sit on concrete columns supported by a concrete mat foundation. A moat is provided around the concrete pad to accommodate horizontal displacements during earthquakes. Figure 2 illustrates the Stack and its support structure.

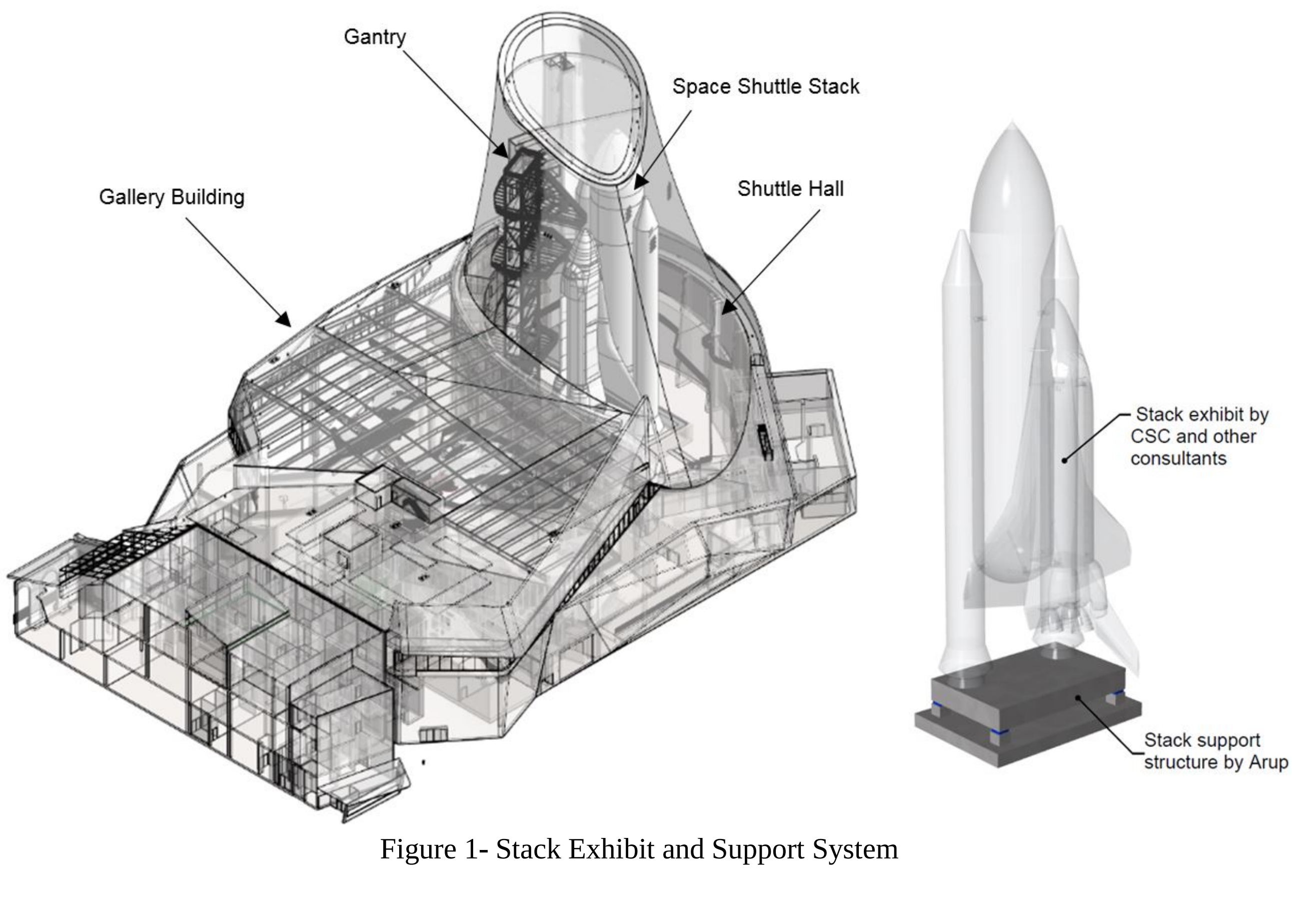


Figure 1- Stack Exhibit and Support System

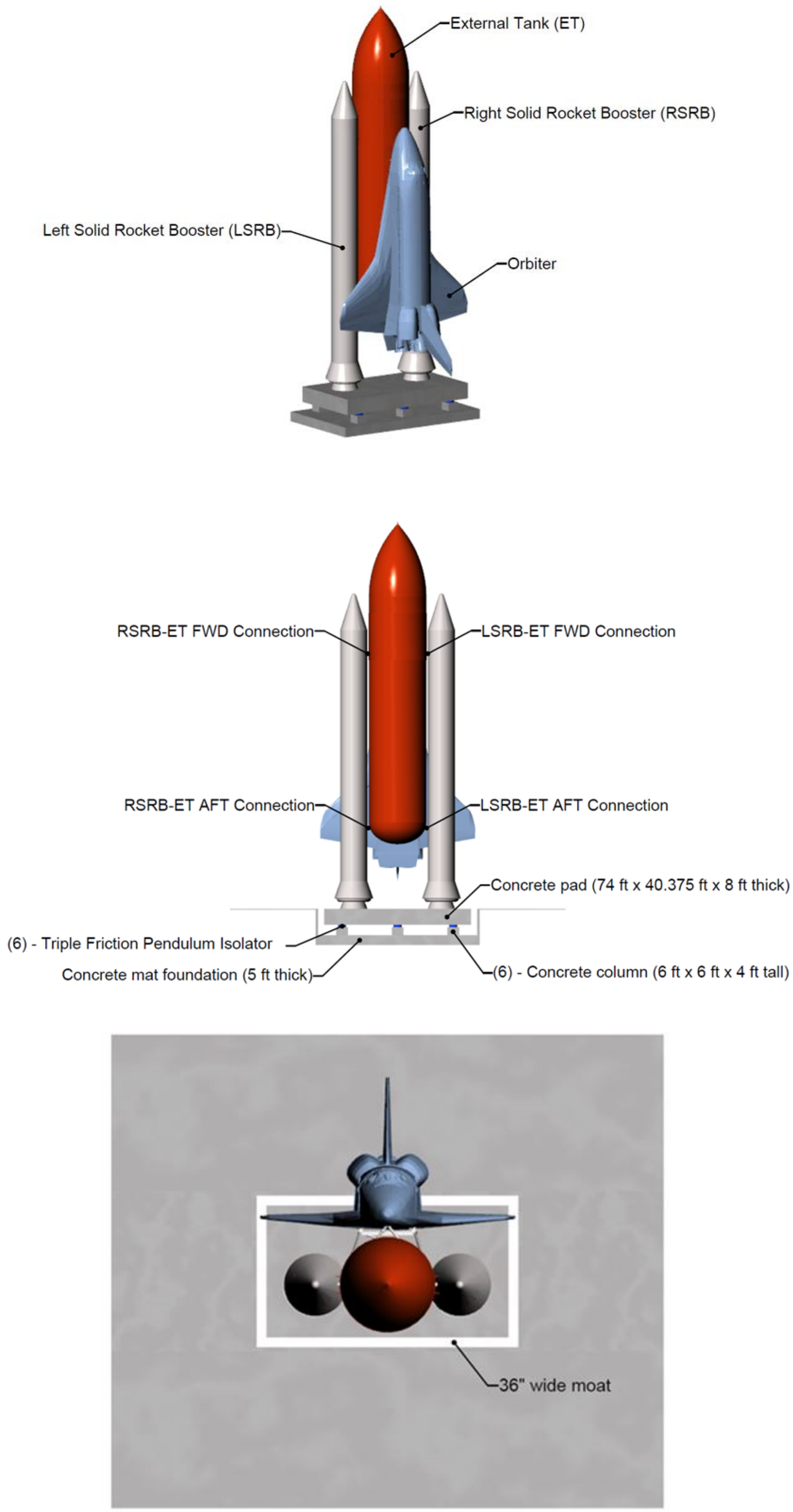


Figure 2 – Enlarged elevation view of the support structure by Arup

2. Design Criteria

One of the primary goals in developing the Samuel Oschin Air and Space Center was to exhibit the Space Shuttle *Endeavour* in launch stack position, in an efficient, cost effective manner without compromising the safety of this irreplaceable piece of space history. The design of the isolation plane (concrete pad), isolators and the elements of the structure below the isolation system (i.e., columns and the foundation) is designed per CBC 2013 with 2014 LA City Amendments to remain elastic under the Maximum Considered Earthquake (MCE) hazard [1]. In recognition of the unique structural features of the Stack, a code minimum design was employed as a starting point with the following additional requirements:

- *Maximum of the response parameters* from 7 MCE ground motions is used for the design of isolation plane and elements of structure below the isolation system.
- *Maximum of the base displacement* response from 7 MCE ground motions is used to verify the maximum displacement demand for the isolators.
- Isolators are sized so that the maximum isolator demand is *smaller than the displacement at threshold of stiffening branch* (Stage 4 to 5, see section 5).
- The total maximum displacement, D_{TM}, is taken as 1.2 times D_M to account for accidental torsion.
- For the SRB attachment to the concrete pad, shear and tension stresses will have separate load paths. No bending or coupling of shear & tension will exist in the design and detailing of the hold down anchors.
- *No uplift* is allowed for the isolators.

The Science Center provided Arup with nodal coordinates, mass and stiffness matrices and damping ratio for the four Stack components for use in representing the Stack dynamic behaviour in an analysis model. These data are based on design loads developed during the space shuttle program and were the criteria used to support the development of the vehicles and to support the 135-mission flight campaign. Arup designed the supporting structure and provided Stack response parameters to the Science Center for verification. The minimum requirements for the Stack that the Science Center must verify to ensure the structural support system design is applicable are:

- The natural frequencies and mode shapes of the assembled Stack matrices in the LS-Dyna analysis model match the dynamic behaviors of the original Stack model.
- Under MCE hazard, the Stack does not demonstrate any nonlinearity – geometric or material. The Stack responses to all 7 MCE ground motion records must be verified to ensure there is no behaviour that would invalidate the mass and stiffness matrices used in the analysis model for support system design

2.1 Loading criteria

Gravity loads consist of the weight of the Stack, the self-weight of the structural components (concrete pad, isolators, etc.), and the weight of architectural finishes. An allowance of 5 psf was made on the concrete pad to account for the weight of the architectural finishes. The weight of the Stack is summarized in Table 1.

Table 1 – Weight of the Stack

Stack component	**Weight**
Orbiter	166 kips
External Tank (ET)	62 kips
Left Solid Rocket Booster (LSRB)	130 kips
Right Solid Rocket Booster (RSRB)	130 kips
Total Stack weight	488 kips

Live loads are loads due to the intended use and occupancy of the area. An allowance of 125 psf was also made on the concrete pad to account for future exhibit flexibility. Site-specific, 5% damped, linear uniform hazard acceleration response spectra and a suite of 7 appropriate ground motion time histories for MCE Level complying with ASCE 7-10 are presented in the report "California Science Center Time History Evaluation Report" dated February 24, 2014 by GeoPentech. The seismic parameters listed in Table 2 are taken from the report.

Table 2 – Seismic mapped acceleration and site class parameters

Site Class	D
Mapped MCE @ short period, S_s	2.062
Mapped MCE @ long period, S_1	0.731
Short-period site coefficient, F_a	1.0
Long-period site coefficient, F_v	1.5
Spectral short-period MCE_R acceleration, S_{MS}	2.062
Spectral long-period MCE_R acceleration, S_{M1}	1.097
Spectral short-period design acceleration, S_{DS}	1.375
Spectral long-period design acceleration, S_{D1}	0.731

3. Stack Modeling

The Stack consists of real flight hardware (artifacts) from the space shuttle program, without any supporting structural steel framing. All load paths through and within the Stack are as designed to support the flight campaign. Forgoing adding any additional supporting structure eliminated the need to run new loads analysis on the Stack, allowing the Science Center and Arup to use flight-certified loads data to verify the Stack can withstand the seismic environment. In the earlier stages, Equivalent Lateral Force and Response Spectrum procedures were used for preliminary structure and isolator designs. Stack Exhibit has no additional structure above the isolated plane (concrete pad), and the Stack is represented by matrices in the analysis model.

The Orbiter is attached to the ET at three locations, one forward and two aft. Each SRB is attached to the ET at four locations, one forward and three aft. To simplify the matrices, two of the aft attachments are treated as a single entity since they share a common mounting point on the ET. This resulted in a total of 9 integration nodes for analysis. As mentioned, each SRB is connected to the isolator pad at four points.

Nonlinear Response History Analysis (NLRHA) procedure is used for the design of the isolator pad and substructure. It is also used for the performance evaluation of the base isolated Stack. The only nonlinear element in the global model is the isolators. The global stiffness of the structure will be updated automatically when the isolator overcomes the friction and starts moving along the spherical surface. This will generate nonlinear force displacement path and simulate the period elongation. In the NLRHA, hysteretic model specified by the isolators will simulate the energy dissipation and provide supplementary damping to the structure.

LS-Dyna was selected for the analysis based on its ability to model the triple friction pendulum isolators and its capability to work with direct matrix input [2]. The Science Center obtained and provided Arup with the mass and stiffness matrices of the four Stack components for use in representing the Stack dynamic behavior in an analysis model. The mass and stiffness matrices are derived from flight verified shuttle math models that were used for all shuttle loads and dynamic analysis throughout the space shuttle development effort and flight campaign. According to the Science Center, the matrices contain the minimum nodes and degrees of freedoms necessary to reliably capture the dynamic behavior of the Stack. Using the matrix import function in LS-Dyna, the matrices were assembled and connected to the support structure being designed by Arup.

Mass eccentricity of the Stack is considered in the LS-Dyna analysis by the distributed nodal mass for the Orbiter, ET, LSRB and RSRB (210 nodes in total). In LS-Dyna, gravity loads for the Stack are applied as point loads distributed over the nodes per their respective mass. These loads are applied using a ramp function pattern with dynamic relaxation of 0.99 equivalent viscous damping. The duration of the ramp function pattern is long enough to see minimal oscillation at the end of dynamic relaxation, before starting the ground motion time history.

The following information from the Science Center was used to create the Stack LS-Dyna model:

- Node IDs and node coordinates for the Orbiter, ET, LSRB and RSRB. There are 210 nodes total.
- Degrees of freedom at each node for the Orbiter, ET, LSRB and RSRB. There are 676 degrees of freedom total.
- Four separate mass matrices corresponding to the degrees of freedom at each node for the Orbiter, ET, LSRB and RSRB.
- Four separate stiffness matrices corresponding to the degrees of freedom at each node for the Orbiter, ET, LSRB and RSRB.
- 9 pairs of integration nodes to be connected to form the connections between Orbiter to ET, LSRB to ET and RSRB to ET. The nodes in each pair have the same coordinates.
- 8 nodes representing the SRB hold down locations. The Stack will be attached to the pad at these locations. Figure 3 graphically show the locations of the 9 pairs of integration nodes and the 8 SRB hold down locations.
- 1% equivalent viscous damping to account for inherent damping in addition to hysteretic damping provided by the isolators.

The analysis and design of the isolator and support structure are based on the above information provided by the Science Center. Once the Stack is assembled, there are experimental methods available for validating the stiffness and mass properties in the provided matrices. Stiffness and mass properties of the connection hardware between the four Stack elements have been idealized into single nodes in the information provided by the Science Center.

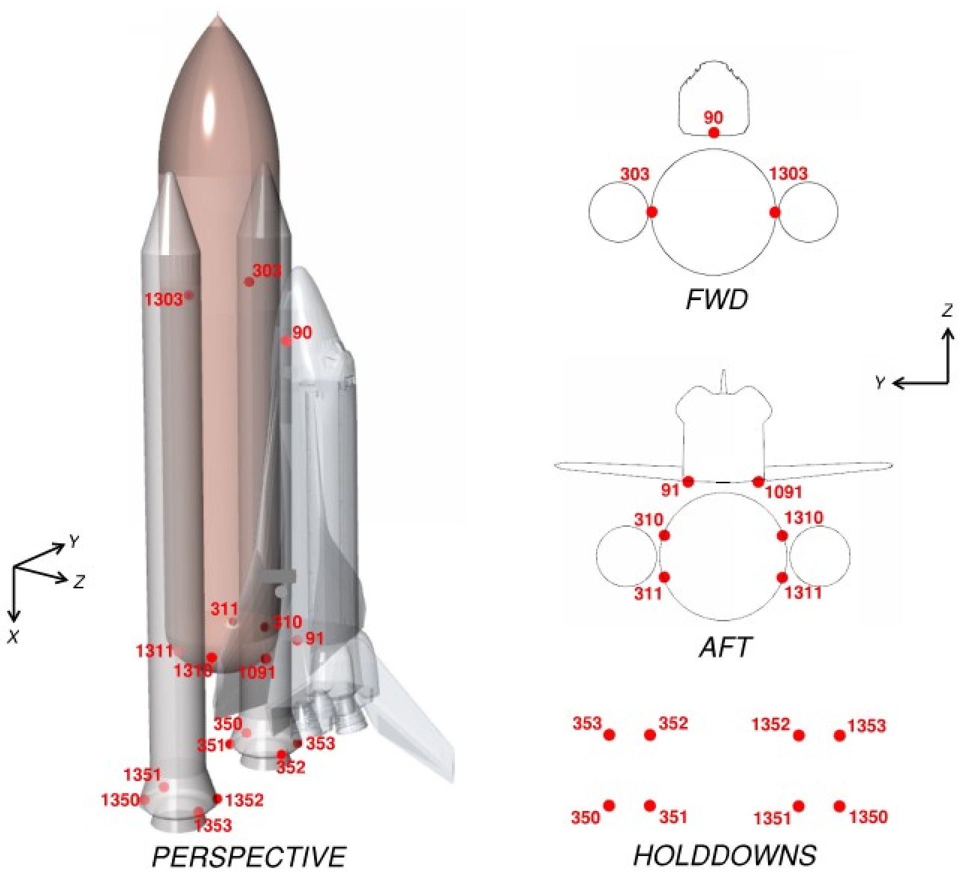


Figure 3 – Connection nodes

LS-Dyna has a feature (*ELEMENT_DIRECT_MATRIX_INPUT) that allows the user to define an element consisting of mass and stiffness matrices in a specified file with direct matrix input format, DMIG. This feature is used to model the Orbiter, ET, LSRB and RSRB in LS-Dyna (see Figure 4).

Since the Orbiter, ET, LSRB and RSRB all have their own separate mass and stiffness matrices, the four components of the Stack are not inherently connected with each other in the LS-Dyna model. The stiff beam elements with zero length was introduced to connect the 9 pairs of integration nodes to create the connections between the four components of the Stack.

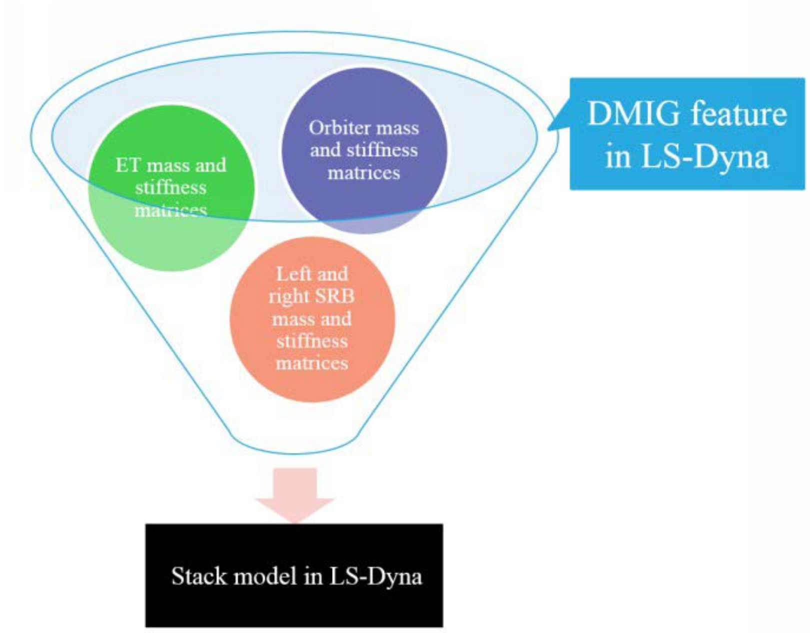


Figure 4 – Modeling the Stack in LS-Dyna

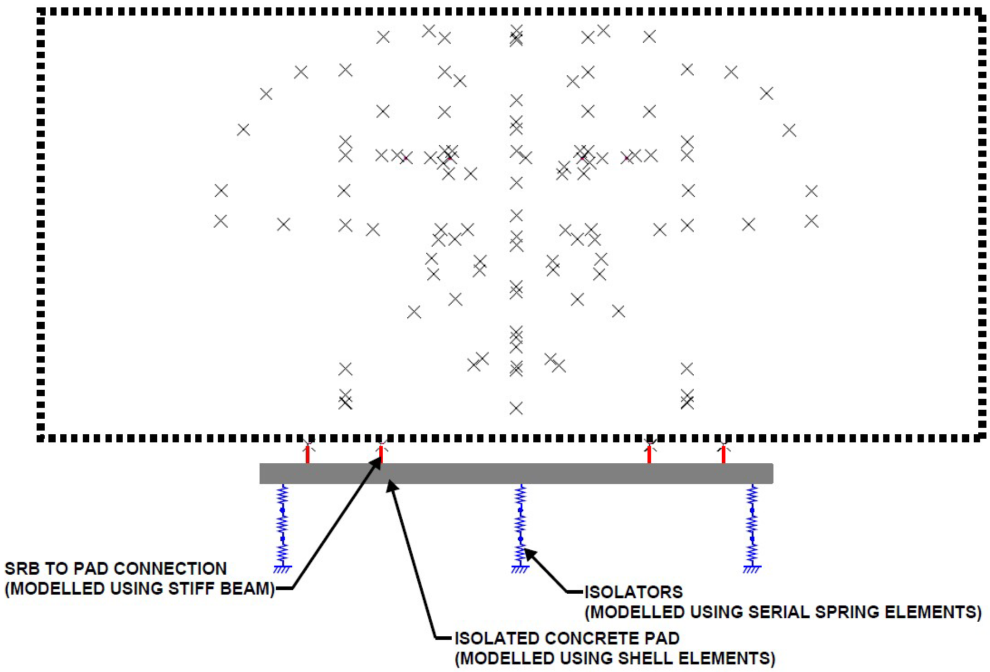


Figure 5 – Enlarged elevation view of the support structure

Conventional methods were used to model the concrete pad and isolators in LS-Dyna. The concrete pad is modelled using 4 node shell elements with orthotropic elastic concrete properties. More in depth information regarding isolator modelling approach is provided in Section 4. The Stack is connected to the concrete pad with 0.5" long, stiff beam elements at the 8 SRB hold down locations. The stiff beams have translational stiffness along its three local axis and rotational stiffness about its three local axis defined to be 1E9 (units in pound and inch). Figure 5 shows an enlarged elevation view of the support structure as modelled in LS-Dyna.

4. Isolator Design and Response Estimates

Parametric studies have been conducted for various isolated periods under various damping scenarios to compute the resulting shear and isolator displacement demands. For the project, it has been selected to use the 4 second isolator which enables to meet performance targets set by the Science Center. Based on the isolator estimates, it was proposed to use one type of triple friction pendulum (TFP) isolator. The notations and the properties of the TFP isolator are summarized in the Figure 6 and Table 3 below.

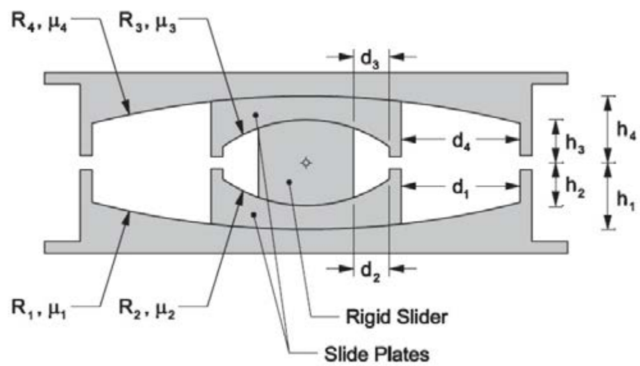


Figure 6 - Notations used for the implementation of the TFP properties

Table 3 - Proposed TFP isolator properties

Nominal friction coefficient	μ_1	μ_2	μ_3	μ_4
	0.07	0.04	0.04	0.08
Radius (in)	R_1	R_2	R_3	R_4
	156	14	14	156
Height (in)	h_1	h_2	h_3	h_4
	6	4.5	4.5	6
Effective radius (in)	R_{eff1}	R_{eff2}	R_{eff3}	R_{eff4}
	150	9.5	9.5	150
Displacement capacity (in)	d_1	d_2	d_3	d_4
	16.5	1.5	1.5	16.5

Considering manufacturing tolerances, prototype test issues such as first-cycle effects, and long-term environmental effects (aging, contamination, etc.), upper and lower bound properties shall be accounted for in the analysis and design. For FTP15641/12-12/8-5 bearing, suggested friction values are summarized in Table 4.

Table 4 - Upper- and lower-bound coefficient

Friction Coefficient	**Nominal**	**Upper-bound**	**Lower-bound**
μ_1	0.070	0.085	0.060
μ_2	0.040	0.055	0.030
μ_3	0.040	0.055	0.030
μ_4	0.080	0.095	0.070

In accordance with ASCE7-10, equivalent lateral force (ELF) procedure was followed to assess the maximum isolator displacement and base shear force. In ELF procedure, iterative calculation is required to converge the assumed displacement to the derived displacement as explained in earlier publications of authors [3, 4]. Summary of the ELF procedure for isolator under MCE and demand, are shown at Table 5 below.

Table 5 – Response estimates using ELF with change in isolator properties

Friction Coefficient	Nominal	Upper-bound	Lower-bound
Maximum Shear Force, F_M/W -[g]	0.161	0.166	0.160
Effective Period, T_M -[s]	4.10	3.80	4.32
Effective Damping, β_M -[%]	28	33	25
Maximum Displacement, D_M -[in]	26.39	23.36	29.25

5. Nonlinear Isolator Modeling

Stiffness and damping varies in the TFP isolator as a result of the various combinations of sliding that occur on the multiple concave surfaces. To conduct nonlinear time history analysis, the variability in stiffness and damping shall be captured properly. A serial spring model presented by Daniel M. Fenz and Michael C. Constantinou was used as a guide to model the TFP isolators in LS-Dyna [5]. LS-Dyna model of the TFP isolator consists of three single concave FP elements connected in series, as shown in Figure 7. The individual elements are constrained to have the same force, but the relative displacements of each are independent. The parameters of the series model for the three elements are summarized in Table 6. In LS-Dyna, the single concave FP element cannot carry axial tension. Therefore, the series model formulation inherently allows uplift.

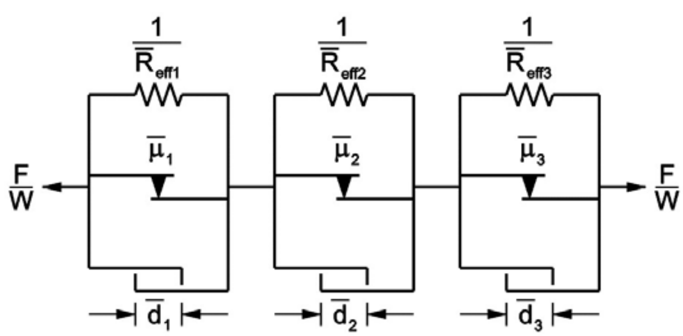


Figure 7 - Three single concave FP elements in series used to model the behaviour of the triple FP bearing

Table 6 - Parameters of serial model used in the TFP modelling

	Coefficient of friction [.]	Radii of curvature [in]	Nominal displacement capacity [in]	Rate parameter [sec/in]
Element 1	0.04	19	5.09	1.27
Element 2	0.07	140.5	15.46	2.71
Element 3	0.08	140.5	15.46	2.71

The theoretical backbone curve showing the different stages of the sliding regime of the proposed TFP isolator design is shown in Figure 8. Table 7 summarizes the different stage of the sliding regime used in the nonlinear modelling of the isolators and in the analysis.

Table 7 - Parameters defining sliding regimes and backbone curve

Regime	Displacement [in]	Horizontal Force [g]	Slope
Sliding Regime 1	0.00" ~ 0.57"	0.040g ~ 0.070g	$1/(R_{eff2} + R_{eff3})$
Sliding Regime 2	0.57" ~ 2.17"	0.070g ~ 0.080g	$1/(R_{eff1} + R_{eff3})$
Sliding Regime 3	2.17" ~ 32.17"	0.080g ~ 0.180g	$1/(R_{eff1} + R_{eff4})$
Sliding Regime 4	32.17" ~ 33.76"	0.180g ~ 0.190g	$1/(R_{eff2} + R_{eff4})$
Sliding Regime 5	33.76" ~ 36.00"	0.190g ~ 0.308g	$1/(R_{eff2} + R_{eff3})$

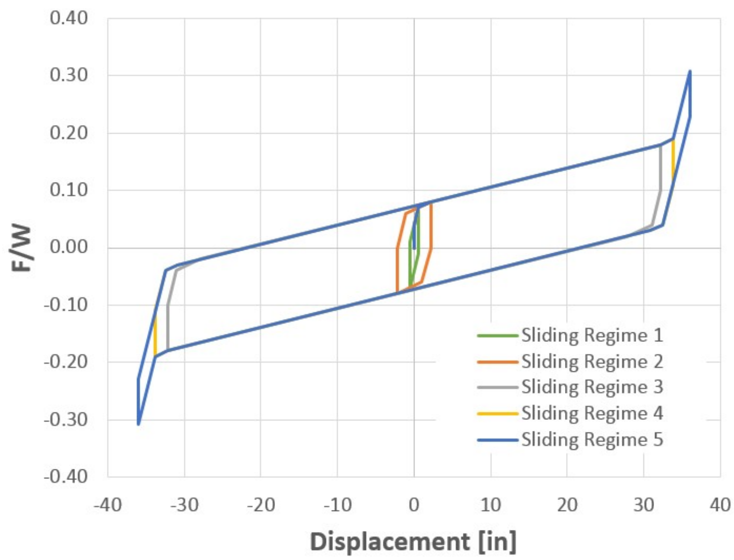


Figure 8 - Theoretical sliding regimes (nominal) of proposed TFP isolator design

To verify the LS-Dyna TFP isolator model, isolator force – displacement relationship from all 7 ground motions were plotted on the theoretical backbone curve. The results match well with the theoretical backbone curve. As an example, Isolator displacement in the xz plane, isolator orbital plot, and isolator force – displacement relationship from ground motion 1 is presented in Figure 9. Nominal friction coefficients and all three components of the ground motions are used in the isolator model verification. The analysis was performed without the retaining ring. Final runs will include the retaining ring. The directionality of the horizontal components of the ground motions are not known (fault normal or fault parallel), therefore the analysis will be performed twice by swapping the horizontal components of each set of ground motion.

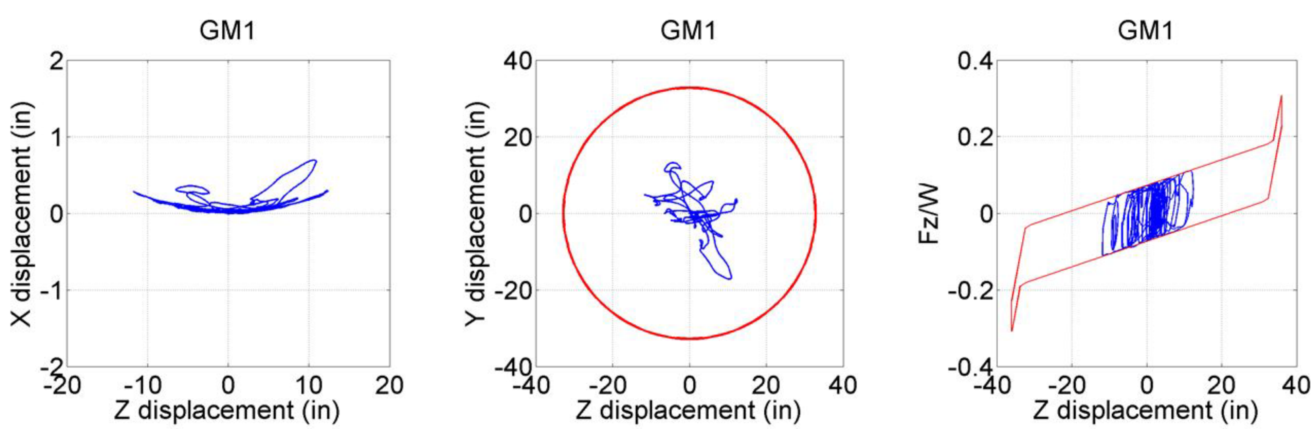


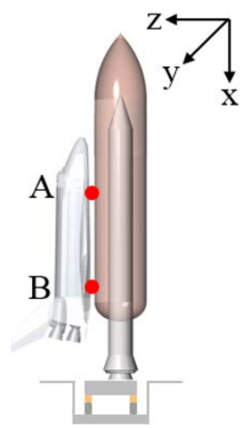
Figure 9 - Theoretical sliding regimes (nominal) of proposed TFP isolator design

6. Analysis Results and Concluding Remarks

Table 8 is a summary of the maximum Stack response when subjected to all 7 ground motions for the (i) fixed base model with both horizontal and vertical ground motion components, (ii) base isolated model with both horizontal and vertical ground motion components and (iii) base isolated model with only the horizontal ground motion components. The plots in Figure 10 illustrate the difference between the fixed base and base isolated Stack models.

Table 8 – Summary of stack response

Response parameter	Dir.	Fixed base H+V	Base isolated H+V	Base Isolated H only
Node A acceleration (g)	x	1.56	1.71	0.62
	y	4.69	1.07	1.08
	z	2.50	0.96	0.77
Node B acceleration (g)	x	1.56	1.35	0.27
	y	1.59	0.68	0.31
	z	1.10	1.01	0.29
Relative displacement between Node A and B (in)	x	1.70	0.56	0.58
	y	10.42	2.28	2.28
	z	13.72	5.44	5.36
Overturning at base stack (kip-ft)	-	61,178	22,461	21,089



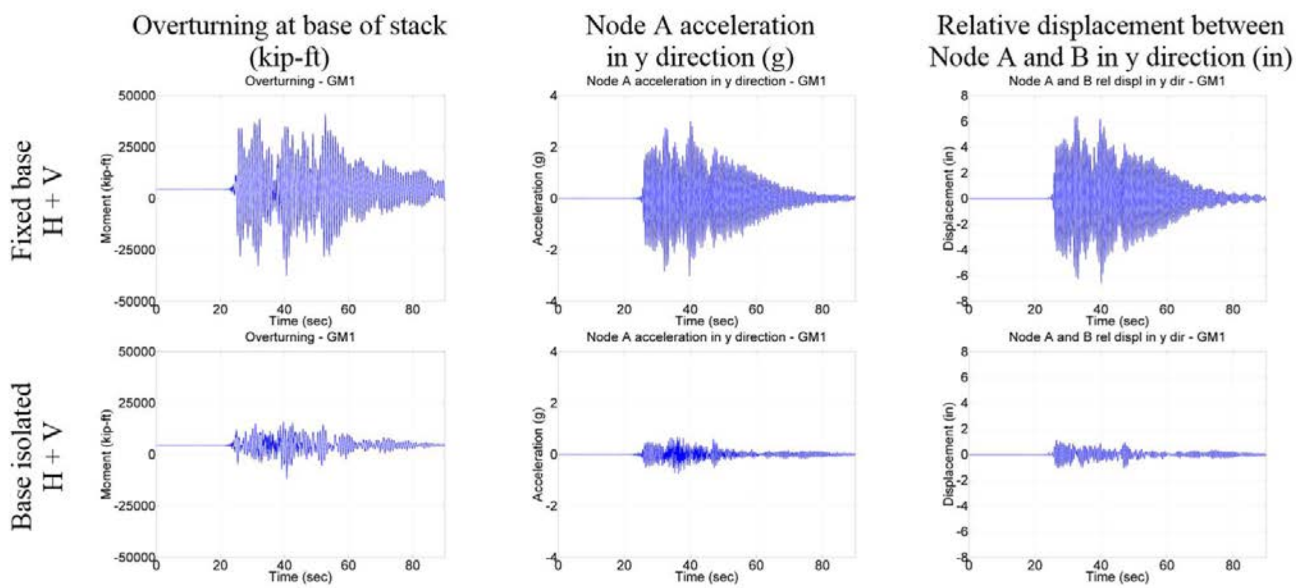


Figure 10 – Comparison between fixed base and base isolated

Whilst the vertical ground motion appears to have little influence on Stack responses such as overturning at the base and the relative deformation between Node A and B, it is important to note some responses do experience significant increase, such as acceleration in the z direction at Node B. This is illustrated in Figure 11. Therefore, in order to accurately capture the Stack response, the vertical ground motion component was considered in the analysis.

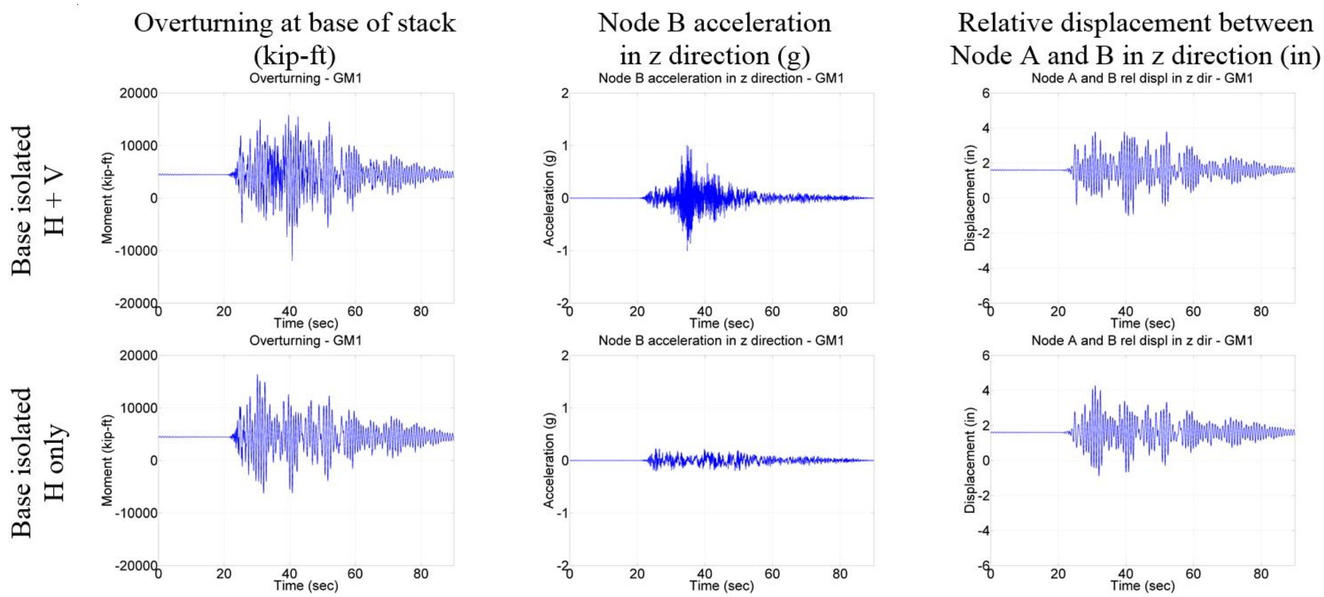


Figure 11 – Comparison between with and without vertical ground motion component

The base isolation reduces the impact of earthquake hazard by achieving significant reduction in the accelerations, displacements and overturning moments at the base when compared to the fixed Stack model, making the decision to implement seismic isolation an obvious choice. Space Shuttle *Endeavour*'s ultimate mission is to inspire current and future generations of explorers and scientists. Seismic isolation technology will help to achieve this ultimate mission.

7. Acknowledgements

Arup would like to acknowledge all the project participants including:
California Science Center Foundation: Owner
Zimmer Gunsul Frasca Architects LLP: Architects
Arup North America Limited: Structural, MEP, Fire/Code Consulting, Acoustics, AV
Geo-Pentech, Inc.: Seismic Hazard Studies
Evidence Design: Exhibit Designers
Bill Novak, Chris Rodgers, and Gary Collier: Space shuttle loads and stress engineers

8. References

[1] ASCE, (2010), *Minimum Design Loads for Buildings and Other Structures (ASCE 7-10)*, American Society of Civil Engineers, Reston, Virginia.

[2] LS-DYNA, *Keyword User's Manual - Version 971*, (2007), Livermore Software Technology Corporation (LSTC), Livermore, CA 94551-5110, USA

[3] Zekioğlu A., Darama H., and Erkus B., (2010), "*Design considerations for a base isolated structure with triple-friction-pendulum isolators: Istanbul Sabiha Gökçen International Airport Terminal Building*", 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, Paper #445, Ontario, Canada

[4] Zekioğlu A., Darama H., Rees S., Pope C. and McGowan R. (2011) "*Performance based seismic design of base isolated Taipei Performing Art Center*", Convention of Structural Engineers Association of California (SEAOC), Las Vegas NV, 21-24 September

[5] Fenz, D.M., and Constantinou, M.C., (2008), "*Modeling triple friction pendulum for response history analysis, Earthquake Spectra*, 24, 1011-1028.