Experiences with Friction Pendulum^{TM} seismic isolation in California

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Abstract

Seismic isolation shines as the top performance system for earthquake resistant structures, having involved a large variety of essential facilities since the late 1980s. Within the available devices, friction pendulum bearings present beneficial dynamic characteristics which are not intrinsically provided by other isolation systems. Developed and engineered by Earthquake Protection Systems, Inc. in California, these bearings have become a popular choice for designers.

This paper firstly presents the experience of Skidmore, Owings & Merrill LLP (SOM) on the design of friction pendulum base isolated buildings, with systems evolving from the single concave to the Triple Friction Pendulum^{TM} (TFP) bearing and with a corresponding history of isolator displacement and base shear demands. The discussion is followed by a case study on a TFP system, in which the client is not only provided with a high performance structure tuned to experience low damage for design earthquake events, but also a more flexible interior unit layout given the reduction on shear wall requirements. Advanced modeling of the bearings and calibration of the design properties are discussed from a practical standpoint, including adjustment of friction coefficients and curvature radii to meet isolator displacement demands and minimum base shear requirements in compliance with the American Standard ASCE 7. Specific issues addressed during the design process and in response to state-of-the-art discussions with the Peer Review Panel, such as the effect of the stiffening range of the bearings or the consideration of rotational ground motion components, are described in depth.

Keywords: enhanced seismic systems, base isolation, Triple Friction Pendulum, performance-based design, rotational ground motions.

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1 SOM experience with Friction Pendulum™ seismic isolation

The incorporation of seismic isolation in SOM building design has been in development since the early 1990's. SOM's first experience with seismic isolation was the 1994 seismic retrofit of the historic 9th District US Court of Appeals (USCOA) building in San Francisco, California (CA). Originally built in 1905, the stone clad, structural steel braced frame structure underwent comprehensive architectural, structural and interior design work to repair earthquake damage, incorporate a seismic isolation retrofit, clarify circulation, and enhance natural light within the interior. The seismic isolation system consists of 256 single concave Friction Pendulum™ isolators placed below the existing structure and above a new foundation system. The isolation system allowed the historic interior finishes to remain as the seismic retrofit requirements to the superstructure were minimized.

The new International Terminal at San Francisco Intentional Airport (SFIA, see Figure 1) was designed in 1995 to incorporate 267 single concave Friction Pendulum™ isolators. In response to the critical nature of the function of a large strategically located airport, the SFIA addressed seismic performance goals with the stated desire to remain operational in the event of a major earthquake, the highest seismic safety requirements ever imposed on an American airport terminal. Adjacent to the San Andreas fault, which produced the historic 1906 7.9 moment magnitude earthquake, the main roof structure and the window wall of the "great hall" were designed to remain essentially elastic under the site specific 1991 California Building Code (CBC) 10% in a 100 year spectra corresponding to a 975 year event. At the time, the International Terminal

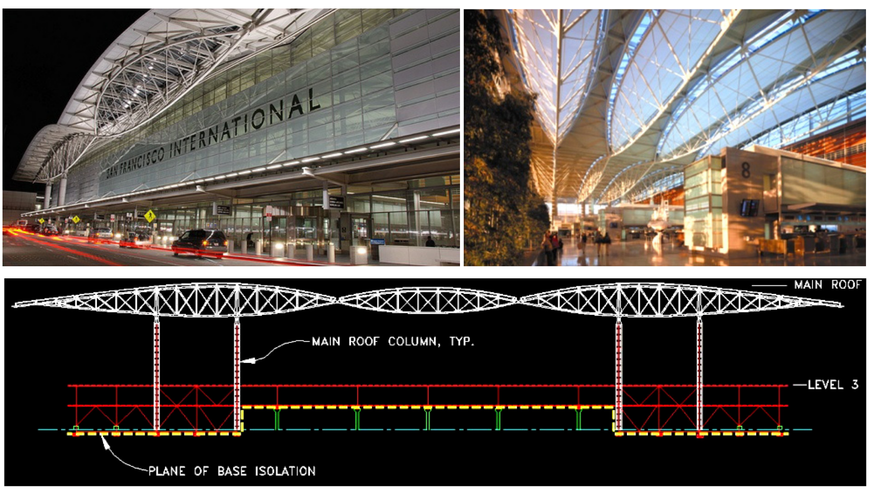


Figure 1: San Francisco International Airport and seismic isolation concept.

Building at over 1 million sq. ft. (93,000 sq. m) was the largest seismically isolated building in the world.

The AboveNet building (AN) located in San Francisco, CA, incorporated 98 single concave Friction Pendulum^{TM} isolators into the 1998 seismic retrofit of a WWII era US Army tank assembly building into a state-of-the-art internet co-location facility. The non-ductile reinforced concrete frame structure was seismically isolated below the ground floor on top cantilevered reinforced concrete piers within the below grade parking structure. The performance goals for the project included the continuous operation of the facility in the event of a MCE level earthquake including full utility backup systems.

The new Cathedral of Christ the Light (CCTL, see Figure 2) in Oakland, CA was completed in 2008 and was the first use of the double concave Friction Pendulum^{TM} bearing. With the goal of the Cathedral to last for centuries, the project was designed to achieve "elastic" behavior under the Design Basis Earthquake (DBE), corresponding to a 10% probability of exceedance in 50 years, with negligible structural damage and "essentially elastic" behavior under the MCE with minimal structural damage. The seismic isolation system allowed the innovative use of modest materials including glued-laminated timber, exposed reinforced concrete, high strength steel, aluminum and glass to provide lightness and luminosity into a symbolic form.

Figure 2: The Cathedral of Christ the Light and double concave bearing concept.

The new San Bernardino Justice Center (SBJC) currently under construction in San Bernardino, CA, is schedule to open in 2014. Situated in close proximity to active faults, the site specific seismic hazard ground motion design criteria was approximately two times greater than minimum mapped CBC building coded requirements in the period range of interest. The courthouse facility features a steel framed superstructure with special moment-resisting frames and 184 supplementary viscous damping devices supported on 69 Triple Friction Pendulum^{TM} seismic isolation bearings, located above the reinforced concrete mat foundation.

Most recently, SOM has designed a future condominium development (8W) to be located in downtown San Francisco which includes two buildings, 6 and 12 stories tall. With the implementation of a common isolation plane with 125 Triple Friction Pendulum™ bearings at ground level, the client is not only provided with a high performance structure tuned to experience low damage for design earthquake events, but also a more flexible interior unit layout given the reduction on shear wall requirements.

Through this history of design experience, the seismic isolation systems have generally evolved from lower period, lower displacement single concave bearings to higher period, higher displacement, triple friction bearings. A comparison of the design parameters of the isolation system is shown in Table 1 and Figure 3. Note the design base shear at the isolation plane does not deviate significantly, typically between 15% and 22% with the exception of the SFIA at 30%.

Table 1: Design parameters of the isolation system for different SOM projects.

PROJECT	USCOA	SFIA	AN	CCTL	SBJC	8W
Friction Pendulum™ System	Single Concave	Single Concave	Single Concave	Double Concave	Triple Friction	Triple Friction
Effective Radius, in (mm)	74 (1880)	88 (2235)	88 (2235)	168 (4267)	300 (7620)	300 (7620)
Bearing Period (s)	2.8	3.0	3.0	4.1	5.5	5.5
Target Friction (μ/W)	7%	5%	5%	5%	9%	8%
Displacement Capacity, in (mm)	14.0 (356)	20.0 (508)	15.0 (381)	30.0 (762)	42.0 (1067)	34.0 (864)
Isolation Plane Base Shear (V/W)	20%	30%	15%	22%	19%	15%
Drift Threshold (Δ/h)	0.2%	1.0%	0.5%	0.5%	1.5%	1.0%

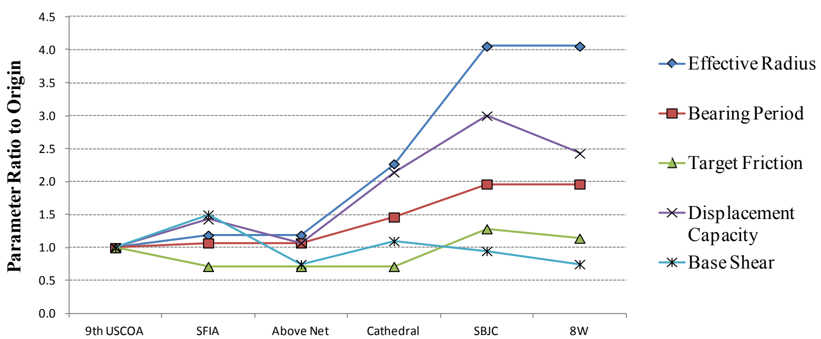
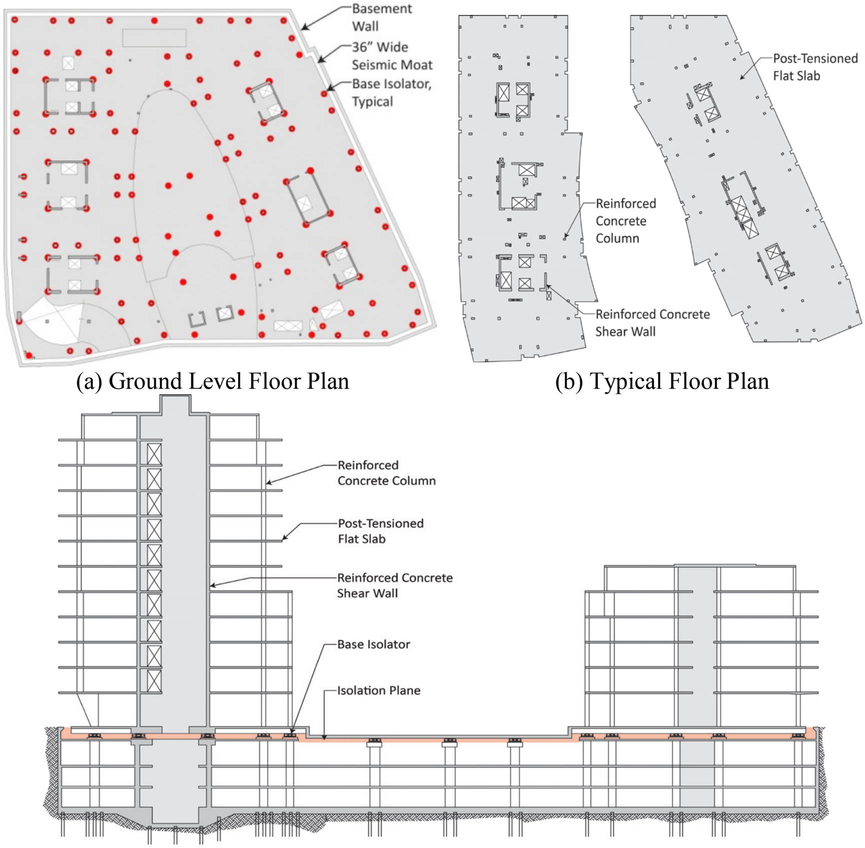


Figure 3: Evolution of the design parameters of the isolation system.

2 A case study on Triple Friction Pendulum™ base isolation

As a result of a collaborative design process, SOM applied a series of innovative methodologies and design solutions to a future condominium development, here referred to as 8W, to be located in downtown San Francisco, California. The project includes two apartment buildings, 12 and 6 stories high. Both buildings share a seismic base isolation system under the ground floor, and three basement levels below. The main superstructure elements are entirely built with concrete, presenting a post-tensioned flat slab system, reinforced concrete columns and reinforced concrete shear wall cores (see Figure 4 for typical floor plans and a building section).



(a) Ground Level Floor Plan (b) Typical Floor Plan

(c) Overall Building Section and Isolation Detail

Figure 4: Building plans and section.

By means of tools such as the Environmental Analysis Tool™, the benefits of an enhanced seismic system could be quantitatively analyzed and presented to the developer for discussion, leading to a high-performance structure with Triple

Friction Pendulum™ seismic isolators (provided by Earthquake Protection Systems, Inc.) with a minimal increase on project budget (2% of construction cost) and robust protection of investment. Base isolation minimizes structural and non-structural damage for design earthquake events, and therefore leads to the lowest values of Expected Annual Loss (see Figure 5 and SEAOC [7]).

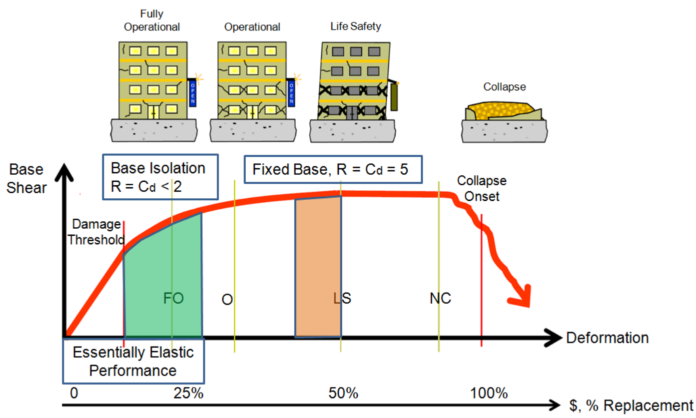


Figure 5: Qualitative performance comparison of fixed base vs. isolated building.

The global structural performance is controlled by the characteristics of the isolation bearings. There are two types of isolation bearings typically considered, Lead-Rubber Bearing (LRB) and Friction Pendulum (FP) systems. Although both types can be designed to a comparable level of performance, the FP system presents several design advantages such as the independency of the fundamental isolated structural periods from the mass of the superstructure and the natural dissipation of any inherent or accidental torsion effects at the isolation plane (Zayas and Low [9]). In addition, with the Triple Friction Pendulum™ (TFP, see Figure 6) bearings, the system can be tuned to an enhanced performance for different earthquake intensity levels. For this project, the asymmetric distribution of mass at the isolation plane due to the presence of two buildings of significantly different heights, and the desire to protect drift and acceleration sensitive non-structural components for service level earthquakes, clearly indicated the suitability of the project for a TFP system. By reducing the torsional demands, a significant amount of shear walls could also be removed. A total of 125 TFP seismic isolation bearings were located under each main gravity column and under each corner of the shear wall cores.

A global structural analysis model (Figure 6) was constructed using the commercial software ETABS (CSI). Nonlinear time history was the analysis procedure utilized (average of 7 earthquake records and maximum of 2 quadrants). Ground motions were spectrally matched to site-specific spectra developed for the site in compliance with ASCE 7-05 Chapter 21.

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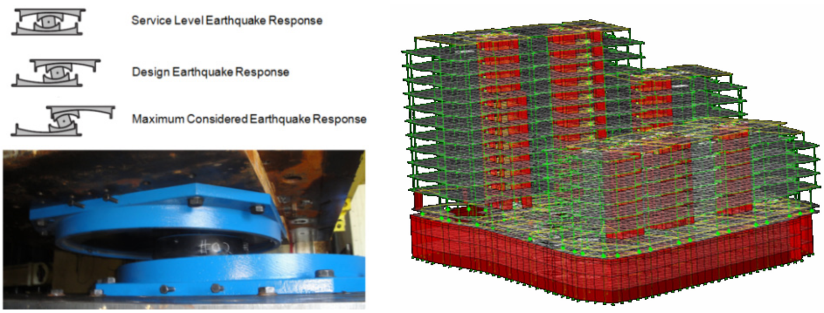


Figure 6: Triple Friction Pendulum™ seismic isolation bearings (left) and Global ETABS Model for the project (right).

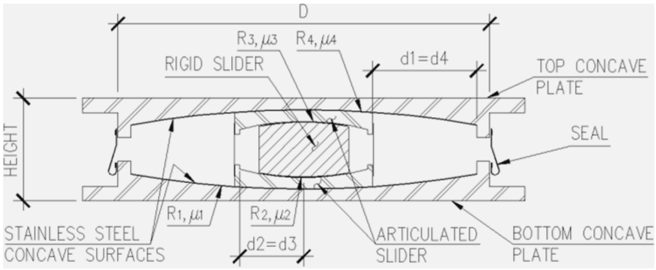


Figure 7: Typical TFP bearing section and design parameters.

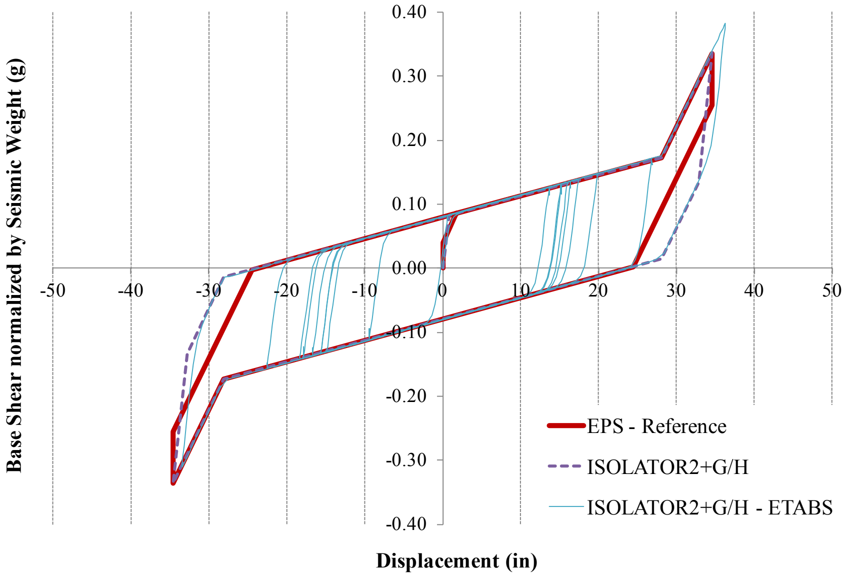


Figure 8: Sample analytical and numerical calibration of the bearings.

The system was designed to lead to an essentially elastic performance under the Design Earthquake (DE, or 10% probability of exceedence in 50 years) as per ASCE 7-05 Chapter 17. The response modification factor for the system is $R = 1.875$ with an overstrength factor for the shear walls equal to $\Omega = 2.5$, and therefore $R/\Omega = 0.75$. For accurate estimation of drifts, forces and displacements, it is fundamental to calibrate the nonlinear link elements utilized to model the isolators so that they match the physical properties provided by the manufacturer. This was performed for the two bearing types selected (high and low axial load), by using a parallel model of ISOLATOR2 and GAP and HOOK link elements (see CSI). The parameters were adjusted for each link in the model as a function of the seismic weight acting on the isolator; bearing type and case of analysis (upper and lower bound friction, uplift, etc.), through automated spreadsheets and scripting. See Figure 8 for a sample adjustment, for further information on advanced modeling of the bearing mechanics refer to Fenz and Constantinou [3] and Sarlis and Constantinou [6].

The design properties finally selected, shown in Table 2 and with a post-elastic sliding regime with 5.5 s period, were governed by the objective of fitting the total maximum displacement within the available seismic moat while keeping the base shear close to the code minimum.

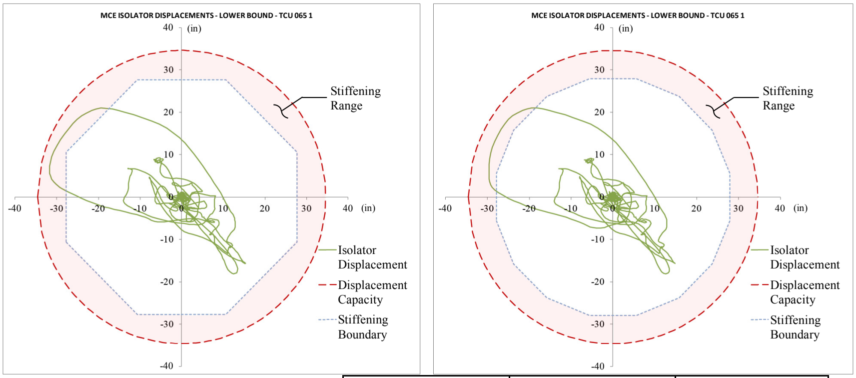
Table 2: Summary table of design properties for the isolation bearings.

BEARING	**FPT 15656/28-28/17-9**			**FPT 15651/24-24/12-8**		
$R_1 = R_4$	156 in ($R_{1,eff} = R_{4,eff}$ = 149 in)			156 in ($R_{1,eff} = R_{4,eff}$ = 150 in)		
$R_2 = R_3$	28 in ($R_{2,eff} = R_{3,eff}$ = 23.5 in)			24 in ($R_{2,eff} = R_{3,eff}$ = 20 in)		
D	60 in			55 in		
HEIGHT, h	20.0 in			17.0 in		
$d_1 = d_4$	14.3 in			13.7 in		
$d_1^* = d_4^*$	13.6 in			13.1 in		
$d_2 = d_3$	4.0 in			5.0 in		
$d_2^* = d_3^*$	3.4 in			4.2 in		
	LB	Target	UB	LB	Target	UB
$\mu^{(1)\,(2)}$	0.064	0.078	0.092	0.065	0.079	0.093
$\mu_1 = \mu_4$	0.070	0.085	0.100	0.070	0.085	0.100
$\mu_2 = \mu_3$	0.030	0.040	0.050	0.030	0.040	0.050
$R_e^{(1)}$	298 in			300 in		

(1) Parameters for equivalent bilinear representation of force-displacement loop.
(2) Value of friction coefficient, μ, is calculated as follows:

$$\mu = \mu_1 - \frac{R_{2,eff}}{R_{1,eff}} \times (\mu_1 - \mu_2)$$

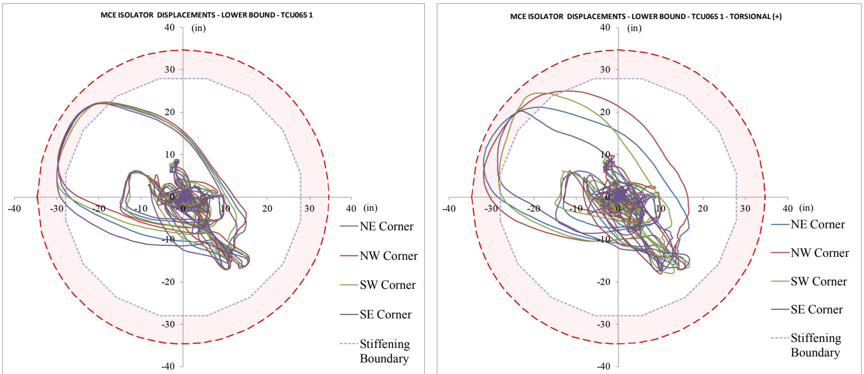
The bearings were designed to reach the displacement capacity of the top and bottom plates (surfaces 1 and 4 on Figure 7) at the Maximum Considered Earthquake (MCE, or 2% probability of exceedence in 50 years) level, producing stiffening of the isolation system by sliding on the higher curvature surfaces of the articulated slider (surfaces 2 and 3 on Figure 7). It is critical to correctly envelope the boundary of the stiffening range by adding several sets of GAP and HOOK elements at different orientations (Fenz and Constantinou [3]) to the analysis model. If this is not properly done, isolator displacement demands would be overestimated whereas other parameters such as uplift and superstructure drift underestimated. A total of 16 degrees of freedom (hexadecagon) were modeled for this case (see Figure 9), which approximated the theoretical circular boundary with less than 2% overestimation, as compared to the 8% overestimation obtained with 8 degrees of freedom (octagon).



	Octagon	Hexadecagon	Δ
Average of Peak Isolator Displacements, in (mm)	33.1 (841)	32.0 (813)	**-3.3 %**

Figure 9: Sample comparison of isolator trajectories at MCE level and lower bound (LB) friction. Stiffening range approximated by a circumscribed octagon (left) versus a hexadecagon (right).

A value of 32.0 in (813 mm) average peak isolator displacement was obtained from analysis, which only included inherent superstructure torsion. Note that accidental torsion only needed to be considered for strength design of the superstructure but not for the bearing displacement given the dynamics of the Friction Pendulum™ system which filters any asymmetric mass distribution at the isolation plane. Complex nonlinear analyses including ground motions with rotational components (developed from the horizontal components per Basu and Whittaker [1]) were then performed to assess the degree of torsional displacement amplification experienced by the system. To that regard, the "stiffening range" acts positively as a rotation-dissipating mechanism which forces the building to have mainly translational components at the isolation plane. This allowed using a 4.3% displacement amplification factor instead of the non-specific 10% factor stated by ASCE 7-05 Chapter 17, which is tailored for the main sliding regime and is overly conservative for stiffening systems. Only one rotational ground motion was applied, with two different orientations and corresponding horizontal components in 2 different quadrants for a total of 4 analyses from where the average torsional amplification was extracted. The total maximum displacement of the isolators was found to be equal to 33.4 in (848 mm), as determined from analysis, being the displacement capacity of the bearings equal to 34.0 in (864 mm). In order to accommodate construction



D_{TM}, no torsional motion, in (mm) (ETABS)	$\Delta_{torsion}$ (SAP2000)	$D_{TM,final} = D_{TM} * (1+\Delta_{torsion})$, in (mm)
32.0 (813)	+4.3%	**33.4 (848)**

Figure 10: Sample comparison of isolator trajectories at MCE level and lower bound (LB) friction. Horizontal components only (left) versus analysis including torsional acceleration (right).

tolerances the seismic moat around the isolation interface was set to 36.0 in (914 mm).

Superstructure drifts obtained from analysis were limited to 0.77% for DE level and upper bound friction properties and 1.15% for MCE and lower bound friction (which governs due to the longer excursion in the stiffening range as compared to the analyses with upper bound friction). This shows an enhanced performance as compared to the 2.0 % Life-Safety drift threshold for a fixed base building at DE indicated on ASCE 7-05 Chapter 12. The maximum DE drift is also 49% under the 1.5% drift limit for base isolated structures stated on Chapter 17. Therefore, although Immediate Occupancy performance, with 0.5% and 1.0% drift limits for DE and MCE respectively as per ASCE 41-06, was not achieved, the building presents a significantly enhanced performance as compared to a code minimum base isolated structure. The peak uplift was found to be 2.4 in (61 mm) at the core corners, within the allowable uplift criteria established for the project (75% of the height of the lip restrainer of the bearings), and it was explicitly calculated with the structural model (Wang *et al.* [8]). See Table 3 for a summary of the main performance parameters.

3 A vision forward

Seismic isolation is often presented by developers and social media as an earthquake-proof system which will experience no damage in a major earthquake. However, it is rare to find examples in which a performance-based assessment has been presented by the engineer to prove the actual level of damage and expected losses. Based on the evolution of design parameters and

Table 3: Global performance summary at DE level (top) and MCE level (bottom), and both upper bound (UB) and lower bound (LB) friction.

	Average of Peak Isolator Displacements, D_{TD}, in (mm)	**Maximum Average of Peak Story Drift Ratios**	**Design Superstructure Base Shear, kip**	**Minimum Code Base Shear, kip**
DE - UB	18.3 (465)	0.77%	7,839 (7.6%)	7,699 (7.5%)
DE - LB	20.2 (513)	0.52%	-	-

	Average of Peak Isolator Displacements, D_{TM}, in (mm)	**Average of Residual Isolator Displacement, in (mm)**	**Maximum Average of Peak Story Drift Ratios**	**Average of Peak Isolator Uplift, in (600 modes)**
MCE – UB	31.3 (795)	2.1 (53)	1.01%	1.42
MCE – LB	33.4 (848)	1.4 (36)	1.15%	2.39

performance criteria for the isolation systems presented in this paper, and being the prescriptive methodology stated on ASCE 7 Chapter 17 (or Eurocode 8 and EN 15129) the day to day criteria for structural engineers, the following question arises: what is the performance actually delivered to the owner by meeting the code minimum level?

Simplifying a comparison of minimum performance requirements for seismically isolated structures between ASCE 7 and Eurocode 8 to their behavior factors at the design earthquake level (475 years return period), both standards establish an essentially elastic performance. For the case of a RC Shear Wall superstructure, the response modification and overstrength factors of ASCE 7 can be combined to yield $R_{\mu} = R/\Omega = 1.875/2.5 = 0.75$, a more conservative value than the maximum behavior factor allowed by the Eurocode 8, q = 1.5. Enhanced performance (essentially elastic behavior, maximum drift ratio of 1.0%, etc.) as compared to the minimum ASCE 7 criteria was set forth for the design of the isolation system here presented for 8W, therefore providing low structural and non structural damage with great degree of confidence. However, in lieu of prescriptive code performance criteria, performance-based studies with damage assessment and loss estimation, based on PEER methodology, should be targeted in future designs to talk in terms of economically quantifiable parameters such as Expected Annual Loss, Probable Maximum Loss and Downtime.

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