The Optimization of Multi-Stage Friction Pendulum Isolators for Loss Mitigation Considering a Range of Seismic Hazard

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ABSTRACT :

An objective in the design of seismically isolated structures is the selection of bearing properties so that optimal performance is achieved over a range of excitations and performance metrics. A challenge in the design of isolation systems is that, to withstand very severe or near-fault motions, bearings often become so large, stiff and strong that they provide little isolation during moderate seismic events. Experimental and numerical investigations are presented to characterize a new multi-stage friction pendulum (FP) isolation bearing, capable of progressively exhibiting different hysteretic properties at various levels of displacement demand. This newly-developed triple pendulum isolator incorporates four concave surfaces and three independent pendulum mechanisms. Through the selection of geometric quantities such as spherical surface radii and slider height, combined with specification of friction coefficients for each interface, pendulum stages can be set to address specific response criteria for moderate, severe and very severe events. The feasibility of targeting these properties to achieve specific performance goals for a range of ground motion intensities and structural dynamic characteristics is investigated. In particular, the tradeoff between limiting very rare isolator displacement demands and inducing high-frequency floor accelerations and inter-story drifts is examined for a range of levels of seismic hazard. Nonlinear dynamic analyses of realistic building systems are presented, including a thorough, probabilistic description of key structural demand parameters suitable for reliability analysis and loss estimation. Recommendations for a design methodology leading to optimal parameters for multi-stage FP bearings given a particular super-structural system and seismic hazard environment are presented. This optimization procedure targets the minimization of loss estimates for over seismic events having a range of mean annual frequencies.

KEYWORDS: Seismic isolation, friction pendulum, performance-based design

1. INTRODUCTION

Since the 1970s, the design of structures to resist earthquake ground motion has benefited tremendously from the application of seismic isolation. This technology provides one of the few means of reducing seismic-induced deformations while simultaneously mitigating high acceleration demands in nonstructural components and contents. As performance-based design has evolved in recent years, a focus on the total seismic performance of structures has emerged in both research and practice. In particular, the consideration of damage due to both seismic induced deformations and accelerations has received attention because of the high-value associated with non-structural components and building contents (Astrella and Whittaker, 2005.)

Because of the importance of contents damage in seismic loss estimation, a consideration of the intensity and frequency content of floor accelerations in base isolated buildings is warranted. Indeed, isolation is often implemented as a means of significantly reducing accelerations transmitted to a structure, particularly with high-value content buildings such as data-storage centers, hospitals, and museums. Existing buildings with brittle appendages such as towers, domes, and cupolas may also be vulnerable to high accelerations. While linear theory of seismic isolation suggests that an isolation system will filter out virtually all acceleration content associated with modes greater than the fundamental mode, the introduction of hysteretic energy dissipation at the isolation interface excites higher-mode accelerations. The effect of nonlinear isolator behavior on the frequency content of floor accelerations has been discussed in Kelly (1981) and Dolce et al. (2003.) This study is concerned with how innovative isolation systems can enhance seismic performance through the reduction of acceleration-induced damage, especially considering high-frequency acceleration content. Such innovative systems will likely see increased development and application as building owners and financial stakeholders look to mitigate content-related damage in buildings over a wide range of seismic hazard levels.

2. MULTI-STAGE FRICTION PENDULUM BEARINGS

To improve the expected behavior of isolated structures subjected to small and moderate seismic events, a series of enhanced friction pendulum bearings have been developed by Earthquake Protection Systems, Inc. of Vallejo, California. These enhanced FP bearings are termed “multi-stage” in this paper because they progressively exhibit different hysteretic properties at different stages of displacement response. A recent addition to the collection of FP bearings is the Triple Pendulum (TP) bearing. This bearing incorporates four concave surfaces and three independent pendulum mechanisms. A section through a typical TP bearing is shown below in Figure 1. The cyclic behavior of TP bearings has been described by Morgan and Mahin (2007) and Fenz and Constantinou (2008a,b.)

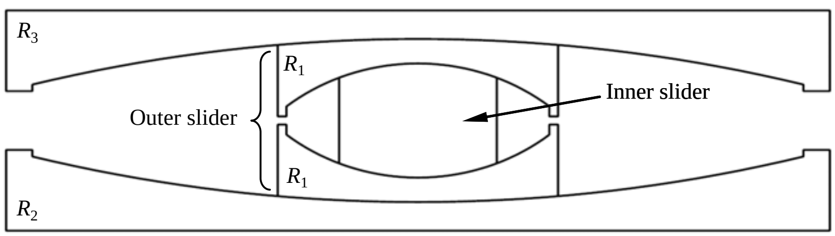

Figure 1: Section through Triple Pendulum bearing (concave radii shown for each dish.)

The outer slider consists of minor concave surfaces (each of radius R_1) on either side of a cylindrical inner slider with a low friction interface (having friction coefficient μ_1) on either end. This forms one pendulum mechanism, and defines the properties of the isolation system under low levels of excitation. The outer slider also consists of sliding interfaces between each outer surface and the major concave surfaces of the bearing. The lower sliding interface (having friction coefficient μ_2) is in contact with a lower concave dish (of radius R_2), forming the second pendulum mechanism. This mechanism defines the primary properties of the isolation system under moderate levels of excitation. The upper sliding interface (having friction coefficient μ_3) is in contact with the upper concave dish (of radius R_3), forming the third pendulum mechanism. The friction coefficient of this third sliding interface is sufficiently large to prevent sliding until an extreme level of excitation occurs. The properties of these three pendulum mechanisms may be selected to optimize the performance of the seismic isolated structure considering multiple levels of seismic hazard.

The isolator stiffness for each stage of sliding may be expressed in terms of effective pendulum lengths. The effective pendulum length L for each of the three pendulum mechanisms is given by

$$L_1 = R_1 - h_1 \,,\, L_2 = R_2 - h_2 \,,\, L_3 = R_3 - h_3 \tag{4}$$

Where R_j is the radius of the jth concave surface as indicated in Figure 1, and h_j is the distance from the center of the jth slider to the concave surface. By taking equilibrium of each pendulum mechanism in the deformed position, and imposing compatibility of rotations, a force-displacement relationship may be generated. Given the above definitions of L_j and μ_j, the monotonic force-displacement behavior of the TP bearing is shown in Figure 2. A complete derivation of the stiffness for each stage of sliding is given in Morgan (2007.) In Figure 2, the effective pendulum length is denoted L_{eff}^{A} where A is a roman numeral between I and V to indicate the sliding stage. The ordinate axis is the normalized isolator shear $\tilde{F} = f / W$. Indicated on this axis are the friction coefficients for each pendulum mechanism. These friction coefficients are ordered such that $\mu_1 < \mu_2 \le \mu_3$. This follows from the design philosophy of the TP bearing, whereby very little frictional resistance is desired for low level excitations, and large frictional resistance (and hence energy dissipation) is desired for intense excitations.

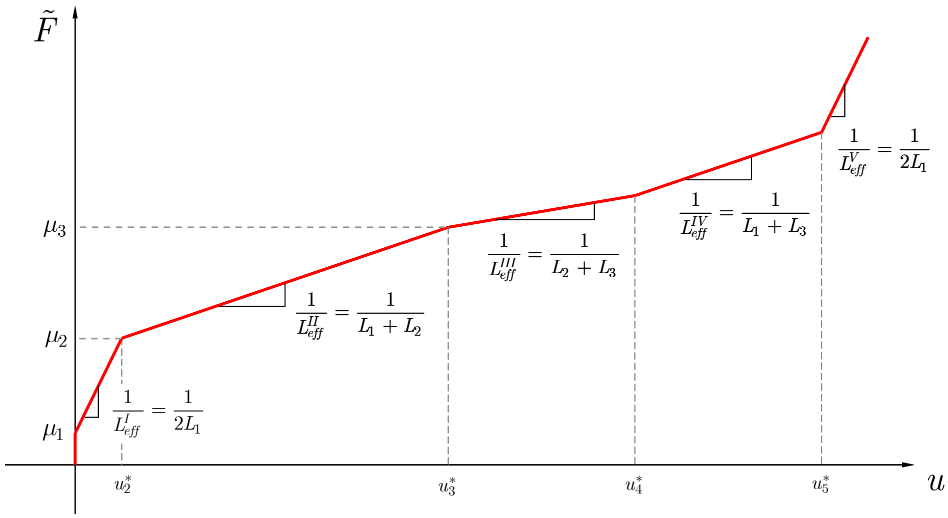

Figure 2: Monotonic normalized force-displacement relationship for the TP bearing (showing sliding stages I through V)

It should be noted that the last two stages of sliding (IV and V) indicate overall stiffening of the isolation system due to the lower and upper concave surfaces reaching their lateral deformation capacities, respectively. The total displacement at which each of these transitions occur is a function of the dish diameter, and may be adjusted as required given the desired cyclic behavior.

3. EXPERIMENTAL CHARACTERIZATION

To characterize the behavior of TP bearings under dynamic excitation, an experimental program was conducted at the Earthquake Simulator Laboratory (or shaking table) at EERC in Richmond, California. This experimental program included: a) harmonic characterization tests at multiple amplitudes and b) earthquake simulation tests considering three historic acceleration records scaled to three levels of intensity. Shaking in one-, two-, and three-directions was considered to evaluate bi-directional behavior, and the effects of vertical acceleration. The specimen consisted of a 1/4-scale three-story steel braced frame building, supported on four scale TP bearings. A section through the scale model TP bearing is shown below in Figure 3, including all relevant geometric properties needed for characterization. Considering the properties of this scale bearing, the model pendulum lengths were L_1 = 2.1”, L_2 = 17.2”, L_3 = 17.2”, respectively. In prototype scale (with length scale = 4, time scale = 2), this corresponds to natural periods in each stage of sliding of T_{I} = 1.32 sec, T_{II} = 2.8 sec, and T_{III} = 3.76 sec for sliding stages I, II, and III, respectively.

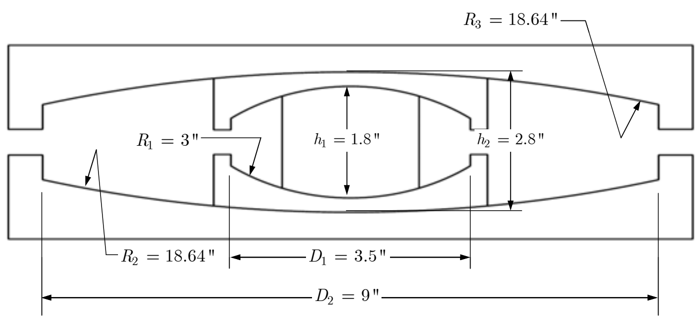

Figure 3: Scale model of TP bearing used as part of the experimental specimen.

To model the cyclic behavior of TP bearings, a three-component series hysteretic spring model was developed to replicate exactly the multi-linear force-displacement relationship shown in Figure 2. Each spring component has essentially rigid-elastic behavior, and parameters of secondary stiffness and yield strength calibrated to represent the stages of sliding I, II, and III. Gap and hook elements are able to replicate the hardening regimes of Stage IV and V. A comparison between the cyclic model and the experimental results are shown for Stage I through IV sliding in Figure 4. The friction coefficients for each of the three interfaces were calibrated my minimizing the difference in dissipated energy between the experiment and the model.

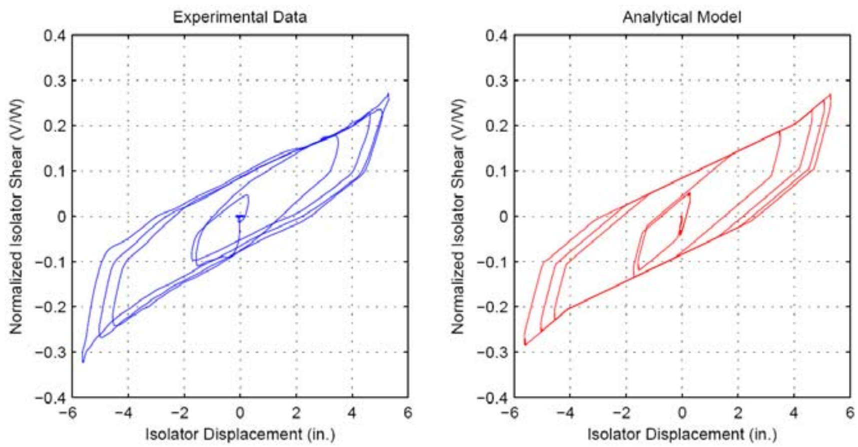

Figure 4: Comparison of cyclic model (left) and experimental results (right) for model TP bearings considering Stage IV sliding

The above-described cyclic model was implemented in nonlinear response-history analysis, and parametric studies were undertaken to assess the sensitivity of important demand parameters to TP characteristics, considering a range of seismic hazard.

4. ANALYTICAL SIMULATIONS

To investigate the performance of buildings isolated with TP bearings, a study was undertaken considering a 3- and 9-story structure. The seismicity of the site was taken as downtown Los Angeles, and the SAC suite of acceleration records was used to characterize the seismic hazard at three return periods: 72-year, 475-year, and 2475-year. The SAC records are described by Somerville et al. (1998.) Both structures were designed according to response-spectrum analysis considering the median SAC 475-year return period spectrum. This procedure leads to fixed-based fundamental periods of the 3- and 9-story structures as indicated in Table 1. Additionally, key properties of the four TP isolators studied in this paper are presented in Table 1. The parameters L and μ are defined above, and U_{limit} are the displacement capacities of each of the three pendulum mechanisms. Here, only the second sliding surface has a displacement limit since this follows the design approach for TP bearings.

Table 1: Properties of model structures

Isolator	L	μ	U_{limit}	T_{fb} (3-Story)	T_{fb} (9-Story)
TP-3-0.10	11", 54", 54"	0.01, 0.042, 0.10	NL, 18", NL	0.71 sec.	1.18 sec.
TP-3-0.25	15", 88", 88"	0.05, 0.075, 0.20	NL, 11", NL	0.71 sec.	1.18 sec.
TP-4-0.10	44", 122", 122"	0.001, 0.035, 0.035	NL, 14.5", NL	0.82 sec.	1.36 sec.
TP-4-0.25	16", 150", 150"	0.02, 0.05, 0.08	NL, 11, NL	0.82 sec.	1.36 sec.

1. NL = No Limit
2. T_{fb} = fixed-based fundamental period

For each level of hazard, four demand parameters were computed: peak interstory drift ratio (PIDR), peak floor acceleration (PFA), peak isolator displacement (U_{iso}), and peak floor spectral acceleration (PFSA.) For a particular model structure, the median demand is computed for each of the above parameters, and plotted as a demand hazard curve. These curves express the 50% probability of experiencing some level of demand given the occurrence of a seismic event having some mean annual frequency (MAF.)

Demand curves for the 3- and 9-story isolated buildings are described in Figures 5 and 6, respectively. Each of these figures describe a family of demand hazard curves corresponding to the four TP isolation systems considered as part of this study. The notation for a TP system indicates the important properties of effective stiffness and equivalent viscous damping. For example, TP-3-0.10 is a TP bearing designed to exhibit an effective period of 3 sec and equivalent viscous damping of 10% critical at some reference displacement (in this case, the 2475-yr isolator displacement).

From the data of Figures 5 and 6, several important observations are made for the 3- and 9-story isolated structures. First, the level of target damping clearly has an effect on the behavior of the superstructure. The PIDR is lowest for the TP-4-0.10, considering all levels of hazard. This system experiences the largest U_{iso} in the 2475-yr event. The TP-4-0.25 has U_{iso} which is about 25% lower than TP-4-0.01, but the PIDR and PFA are increased as a result of the increased damping. This illustrates the tradeoff between increased damping and superstructure performance. It is noteworthy that the TP bearings achieve effective isolation across a range of seismic hazard, since peak response quantities show significant reduction for low compared to high seismic hazard. This may not always be the case for bilinear hysteretic isolation systems, particularly for acceleration demands, details of which may be found in Morgan and Mahin [2007.]

It is interesting to focus on the cases TP-3-0.1 and TP-4-0.25. The isolator displacements for these two systems are nearly identical for all levels of seismic hazard. However, for both 3- and 9-story structures, the superstructure demands differ between the two. Considering the most frequent earthquake (T_R = 72 years), it is clear that TP-3-0.1 results in lower PIDR and PFA compared to TP-4-0.25. This indicates the favorability of an isolation system which controls displacement by reducing the isolated period rather than by increasing the damping. However, for all isolation systems considered, the structural performance should be considered exceptional since PIDR demands are less that 0.5% in all most the most rare events. This corresponds roughly to serviceable performance considering structural and nonstructural components.

The parameters for TP bearings appear to have en effect of response of non-rigid nonstructural components. By examining the data for PFSA, it is clear that the damping has a significant effect on the frequency content of floor accelerations. The lowest PFSA demands occur for the TP-4-0.10, which is expected given the combination of period elongation and low damping in this system. For the 3-story structure, there is some decrease in PFSA in the frequent earthquake by using a TP-3-0.10 bearing instead of a TP-4-0.25 bearing. This benefit decreases for the 9-story structure, indicating less sensitivity of floor spectra to isolation damping as the structure becomes more flexible.

A final observation of the results presented here is the importance of period separation in isolated structures. Conventional design of isolated buildings places importance on stiffening of the superstructure to achieve effective protection of the structure and it's contents. However, for the cases studies here, the period separation is not necessarily dramatic. Consider the 9-story isolated building. From Table 1, the fixed-base period of the structure on TP-3 and TP-4 bearings is 1.18 sec 1.36 sec, respectively. Even for these moderately flexible structure, the isolation systems considered here provide clear protection of the structure. PIDR demands for the 9-story building do not exceed 0.8% even for the 2475-year event, which is near elastic behavior for many structural systems. Further study is needed, but there appears to be promise in applying TP isolation devices to tall, flexible structures to achieve improved seismic response.

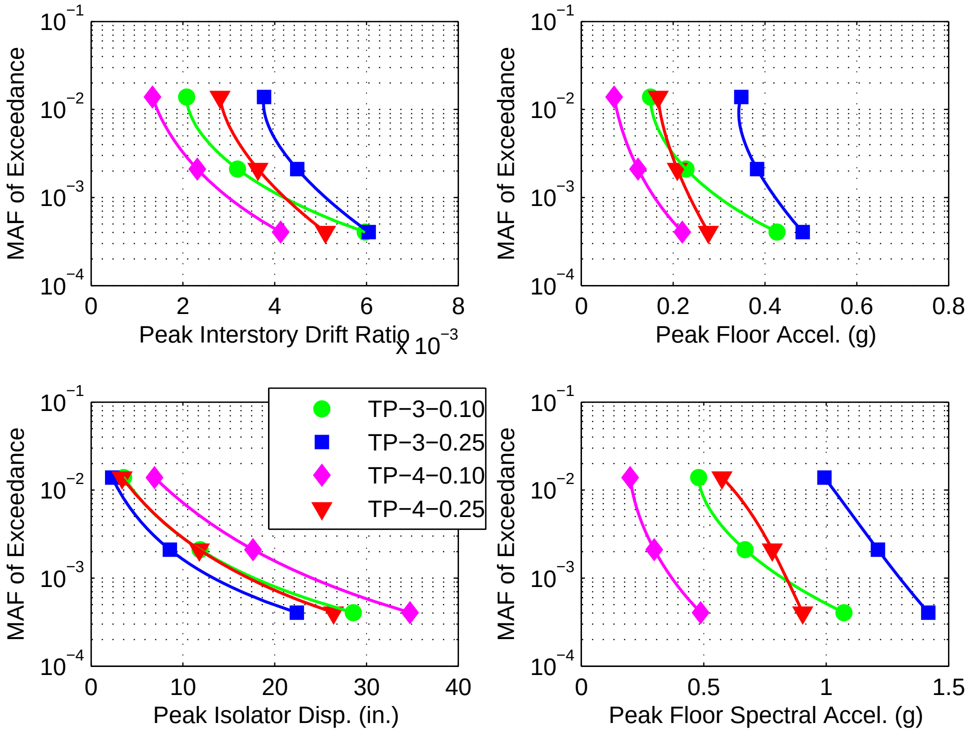

Figure 5: Median demand hazard curves for 3-story building on TP isolation system

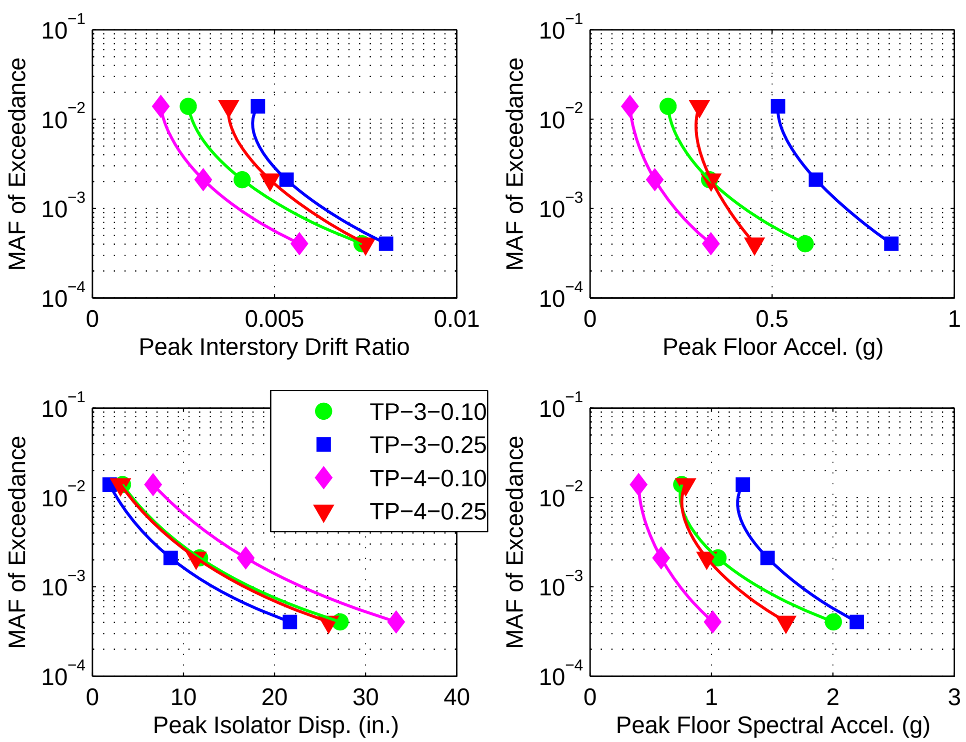

Figure 6: Median demand hazard curves for 9-story building on TP isolation system

5. CONCLUSIONS

The studies presented highlight a potential dilemma in the design of base isolated structures to simultaneously achieve stable performance of the bearings in a very rare seismic event and functionality of the superstructure in an occasional event. This stems from the desire to limit displacements through the introduction of large amounts of hysteretic energy dissipation. Since this form of energy dissipation is highly effective at small displacements, and less effective with increasing displacements, the cyclic behavior of traditional isolation systems does not efficiently meet the performance objectives of isolated buildings.

To address this dilemma, a new class of isolation devices has been developed. These multi-stage friction pendulum bearings have the advantage of three independent pendulum mechanisms whose stiffness and damping can be selected based on multiple levels of seismic demand. The benefits of these devices is demonstrated in this study by looking at the tradeoff between isolator displacement and peak floor acceleration and floor spectra. All four TP isolation systems presented in this study provide effective isolation for the model 3- and 9-story buildings studied, based on computed drift and floor acceleration response. Whereas increased damping leads to reduction at the isolation level, this also leads to modest increases in acceleration and drift demands in the superstructure. It is apparent that, for protection of structural and non-structural elements in frequent earthquakes, the tradeoff between elongation of period and increased damping through friction should be evaluated carefully. For the studies presented here, there appears to be some benefit to reducing the target damping and stiffening the isolation system to limit isolator displacement demands. However, this result may not be general for a wide-class of structural systems, and further study is warranted.

Based on the results presented here, there appears to be promise in applying TP isolation devices to tall, flexible structures to achieve improved seismic response. Even the 9-story structure achieved serviceability-level response in the 2475-year seismic event, far exceeding the expected performance of conventional structures.

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