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THE USE OF SEISMIC PERFORMANCE CLASSIFICATIONS IN THE OPTIMIZATION OF BASE ISOLATED BUILDINGS

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ABSTRACT

In the design of structures to mitigate earthquake hazard, a key ingredient is the definition of the target seismic performance objective for a particular facility. It is generally accepted that target performance is a function of the classification of the structure and its level of importance to either the institutional owner or the general welfare of society. Traditionally, seismic performance goals have been explicitly targeted for only one particular level of earthquake hazard without consideration of larger or smaller earthquakes. However, commentary to model building codes indicate that there is an expectation that structures will achieve distinct performance objected over a range of seismic demands. In the design of structures to meet such complex (i.e. multi-event) performance objectives, a reliability-based methodology is necessary that treats each distinct earthquake hazard and the associated target performance. This paper develops such a methodology, and defines Seismic Performance Classifications (SPC) to categorize structures which meet complex performance objectives. Such a classification allows building stakeholders to define target performance as a function of distinct damage states for distinct seismic intensities. This methodology is then applied to several classes of base isolated buildings to assess which properties of isolation devices have a significant effect on multi-event seismic performance. Conclusions are drawn as to the relative performance benefits of linear isolation devices with nonlinear viscous and hysteretic damping mechanisms, and innovative multi-stage friction pendulum isolators.

Introduction

For over 30 years, 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 non-structural 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

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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 by Kelly (1981) and Dolce and Cardone (2003), among others. This study is concerned with how innovative isolation systems can enhance seismic performance through the reduction of both drift- and acceleration-induced damage, particularly in moderate seismic events for which functional performance is assumed. 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.

Analytical Simulations

Three classes of isolated buildings are considered in this study: a linear viscous (LV) isolation system, a bilinear (BL) hysteretic isolation system, and the above-described triple pendulum (TP) system. The design of the BL and TP isolation systems is such that their effective period and equivalent viscous damping at the median MCE linear viscous isolator displacements were equal to the target. The supported building is modelled as a three-story brace frame structure designed to be elastic for the median DBE force level. This results in a superstructure which is identical for all bearing types since the equivalent linear properties are essentially equivalent. In this paper, isolation systems are identified as “XX-Y-ZZ” where XX is the isolator type (LV, BL, or TP), Y is the effective period in seconds (3 or 4), and ZZ is the level of effective damping in % critical (10 or 25).

Ground Motions

To both facilitate the development of statistical descriptions of EDPs and to consider a variety of seismic characteristics, an ensemble of ground motions was selected to represent possible realizations of ground motion at a site. As part of the SAC Steel Project, several ensembles of ground motions were developed for the Los Angeles basin. A total of 60 records were considered, 20 from each of 3 bins: SLE - Service Level Event (T_R = 72-yr), DBE - Design Basis Event (T_R = 475-yr) and MCE - Maximum Considered Event (T_R = 2475-yr). Further details of the development of the SAC ground motions are described by Somerville et al (1998).

In selecting design parameters for a particular class of isolation systems, we first must define the required inputs. The response of an equivalent linear isolated SDOF structure may be characterized based on three parameters: effective period T_{eff}, effective viscous damping ζ_{eff}, and the level of seismic hazard. In this study, four sets of effective isolator properties are considered: two at moderate and long periods (T_{eff} = 3 sec and 4 sec, respectively), each having low and high damping (10% and 25% critical, respectively.) Equivalence amongst isolation systems is defined as each having the same effective period and effective viscous damping at a maximum isolator displacement resulting from the occurrence of an earthquake having a return period of 2475-years. For an SDOF system, the maximum isolator displacement u_0 is simply the spectral displacement at a given effective period and damping, $D_{T_R}\left(T_{eff},\zeta_{eff}\right)$, where T_R is the return period of the earthquake for which the spectrum was developed.

Superstructure Design

For each isolation system considered, the design of the superstructure is based on an assumed steel braced frame lateral system, and targeted elastic behavior in the DBE. A shear-type structure is assumed in which each floor level is represented by a rigid floor whose mass is arbitrarily set to unity, and inter-story braces are represented by linear springs. A force-based design procedure is used that leads to an estimate of elastic story stiffness, and hence mode shapes and natural frequencies. Note that, since the structure is assumed to remain elastic, only the isolation system includes the explicit nonlinear hysteretic properties. While this limits the validity of deformation response estimates which exceed the assumed yield inter-story drift, the purpose of this study is to compare the effects of isolation system behavior, and these comparisons remain consistent.

The above-described elastic design approach is applied to the three-story shear building. $T_{n,super}$ refers to the building above the isolation interface whereas $T_{n,iso}$ refers to the entire isolated building.

Table 1: Summary of first three natural periods of all three-story shear buildings

	T_{eff} = 3 s, ζ_{eff} = 0.10		T_{eff} = 3 s, ζ_{eff} = 0.25		T_{eff} = 4 s, ζ_{eff} = 0.10		T_{eff} = 4 s, ζ_{eff} = 0.25	
Mode	$T_{n,super}$	$T_{n,iso}$	$T_{n,super}$	$T_{n,iso}$	$T_{n,super}$	$T_{n,iso}$	$T_{n,super}$	$T_{n,iso}$
1	0.74 s	3.06 s	0.85 s	3.08 s	0.85 s	4.06 s	0.98 s	4.08 s
2	0.30 s	0.46 s	0.35 s	0.53 s	0.35 s	0.54 s	0.40 s	0.62 s
3	0.19 s	0.26 s	0.22 s	0.29 s	0.22 s	0.30 s	0.25 s	0.34 s

Linear Viscous Isolation Systems (LV)

Considering linear viscous isolation systems, the computation of isolation system parameters is quite straight-forward, and is summarized here for completeness. The parameters characterizing a LV system are the isolator stiffness, k_{iso}, and the damping coefficient, c_d. It is convenient to normalize these parameters by the supported seismic weight W, giving weight-independent parameters

$$\bar{k}_{iso}=\frac{k_{iso}}{W},\quad \bar{c}_d=\frac{c_d}{W} \tag{1}$$

Given a target effective stiffness and damping, T_{eff} and ζ_{eff}, the necessary normalized isolation system parameters are computed from classical SDOF dynamics as

$$\bar{k}_{iso}=\frac{4\pi^2}{T_{eff}^2 g},\quad \bar{c}_d=\frac{4\pi\zeta_{eff}}{T_{eff}\,g} \tag{2}$$

As expected, these parameters are independent of the assumed displacement, and therefore, of the considered earthquake return period T_R. A summary of properties for all LV isolation systems is listed in Table 2. Sample cyclic behavior for an LV system is shown in Figure 1.

Bilinear Hysteretic Isolation Systems (BL)

Consider an isolation system characterized by a linear isolator in combination with a bilinear hysteretic energy dissipation element. Such dissipation mechanisms may be due to metallic yielding or Coulomb-type friction. As before, the linear isolator is characterized by the normalized stiffness $\bar{k}_{iso}$. The bilinear element is characterized by the yield displacement u_y and normalized yield force $\bar{f}_y$, which is the actual yield force divided by the supported weight. To develop bilinear parameters which give effective linear properties equal to those for the LV system, it is important to define these effective properties. The general definitions of effective properties outlined in ASCE 7 (2005) are adopted here. For a bilinear system, the effective stiffness and damping at some displacement u_0 may be expressed using normalized parameters as

$$\bar{k}_{eff} = \frac{\bar{f}\left(u_0\right)}{u_0}, \quad \zeta_{eff} = \frac{2\bar{f}_y\left(u_0 - u_y\right)}{\pi \bar{k}_{eff} u_0^2} \tag{3)a,b}$$

First, we recognize that the effective stiffness of the isolated structure may be expressed as $\bar{k}_{eff} = 4\pi^2 / T_{eff}^2 g$. Substituting this into Eq. (3)b and solving for the normalized yield force gives

$$\bar{f}_y = \frac{2\pi^3 \zeta_{eff} u_0^2}{T_{eff}^2 g\left(u_0 - u_y\right)} \tag{4}$$

A suitable yield displacement u_y may be assumed depending on the type dissipation mechanism, and it is treated here as a given or assumed parameter. As a result, the normalized yield force $\bar{f}_y$ is determined completely from the input parameters identified earlier, namely effective stiffness, effective damping, and the isolator displacement which is taken directly from a response spectrum at some return period T_R. The normalized force output by the isolation system at displacement u_0 can be expressed as

$$\bar{f}\left(u_0\right) = \bar{f}_y + \bar{k}_{iso}\left(u_0 - u_y\right) \tag{5}$$

Substituting Eq. (4) into Eq. (5) and solving for the normalized isolator stiffness gives

$$\bar{k}_{iso} = \frac{4\pi^2 u_0}{T_{eff}^2 g\left(u_0 - u_y\right)}\left[1 - \frac{\pi \zeta_{eff} u_0}{2\left(u_0 - u_y\right)}\right] \tag{6}$$

Recall that $u_0 = D_{T_R}\left(T_{eff}, \zeta_{eff}\right)$, or the spectral displacement given the target effective properties and a spectrum at some return period T_R. Hence, both the isolator stiffness and yield force of the bilinear element are uniquely defined given our target effective properties and a response spectrum at some desired return period T_R. A summary of properties for all BL isolation systems is listed inTable 2. Sample cyclic behavior for a BL system is shown in Figure 1.

Triple Pendulum Isolation Systems (TP)

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. The analytical behavior of TP bearings, including an suitable cyclic model with experimental verification, has been reported by Morgan (2007) and Fenz and Constantinou (2008a,b). A feature of the TP isolation system is the multiple geometric and frictional parameters that characterize its cyclic behavior. The parameters open to selection by the designer include: effective spherical radii (L_1, L_2, L_3), pendulum displacement capacities ($\bar{u}_1, \bar{u}_2, \bar{u}_3$), and friction coefficients (μ_1, μ_2, μ_3). Here, only the second pendulum mechanism is assumed to reach its displacement limit so as to not engage stiffening associated with the final sliding Stage, which is reserved for deformations approaching the deformation capacity of the bearing. In practice, the TP parameters do not assume arbitrary and necessarily distinct values, but are selected based on standard manufactured sizes and specialized to the particular seismic environment. In this study, parameters are selected to achieve practical design properties which are equivalent to the linear viscous and bilinear hysteretic isolation systems described in the previous sections. The validity of effective linear properties to predict nonlinear response of TP bearings has been shown in [15]. A summary of properties for all isolation systems is listed in Table 2. Sample cyclic behavior for a TP system is shown in Figure 1

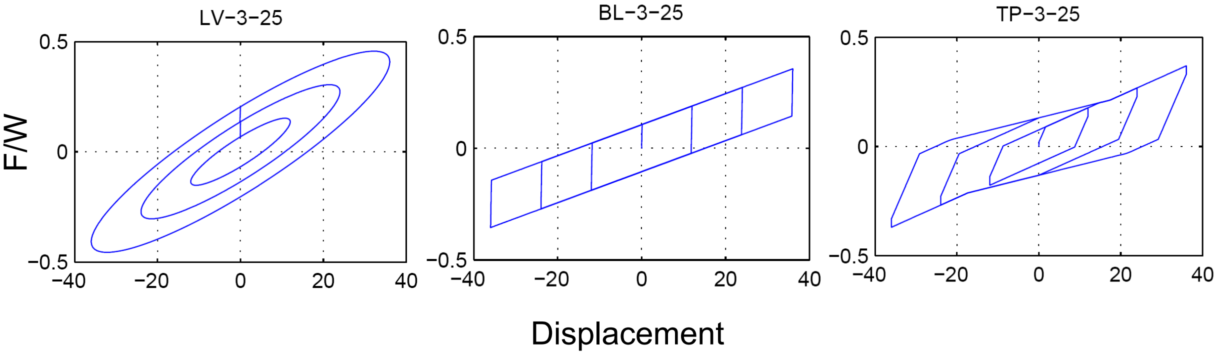

Figure 1: Sample cyclic behavior for all isolation systems having T_{eff} = 3 sec, ζ_{eff} = 0.25

Table 2: Summary of isolation system properties

		Linear Viscous (LV)		Bilinear Hysteretic (BL)		Triple Pendulum (TP)		
T_{eff}	ζ_{eff}	$\bar{k}_{iso}^{1}$	$\bar{c}_d^{2}$	$\bar{k}_{iso}^{1}$	$\bar{f}_y^{3}$	L_{eff}	μ	$\bar{u}$
3 sec	0.10	0.01135	0.00108	0.00960	0.05460	24" / 63" / 63"	0.01 / 0.06 / 0.14	13.8"
3 sec	0.25	0.01135	0.00271	0.00691	0.10520	12" / 114" / 114"	0.02 / 0.09 / 0.20	13.1"
4 sec	0.10	0.00639	0.00081	0.00540	0.03240	44" / 105" / 105"	0.01 / 0.035 / 0.065	17.5"
4 sec	0.25	0.06386	0.00203	0.00388	0.05667	16" / 156" / 156"	0.02 / 0.05 / 0.08	11.0"

Units: ^{1}1/in, ^{2}sec/in, ^{3}nondimensional

Probabilistic Evaluation

The section provides a specific framework within which the previously-described three- and nine-story isolated buildings are evaluated. First, the concept of a multi-objective Seismic

Performance Classification (SPC) is defined. This definition is contrasted with the procedures contained in modern building code provisions, which explicitly consider a single performance objective at a single level of seismic hazard. Since an important component of determination of the SPC for a facility is the limits defining damage state transitions, explicit limit state vectors are defined for each damage state considered. Lastly, a set of SPC designations is defined in the multi-objective context. These definitions are applied to the results of the isolated building analyses to compute reliability estimates.

Seismic Performance Classification (SPC)

Consider a vector of engineering demand parameters (EDPs) given the occurrence of a seismic event having a return period of T_R years. This vector of n EDPs, $\mathbf{X} \in \mathrm{R}^n$, is considered random and characterized by some distribution and associated multivariate probability density function (PDF) $f_{\mathbf{X}}(\mathbf{x})$. The demands are assumed to be jointly lognormal (McGuire 2004, Aslani and Miranda 2005.) We can also define a vector of deterministic limit states $\overline{\mathbf{x}}_R^{\Upsilon} \in \mathrm{R}^n$ whose entries define the joint limits on $\mathbf{X}$ to meet Damage State (DS) Υ in an earthquake having return period T_R. The variable Υ may take on descriptive values that indicate the level of damage (i.e. DS-F = Functional, DS-IO = Immediate Occupancy, DS-LS = Life Safety, etc.) It follows that, given the occurrence of an earthquake, the condition of a structure suffering damage classified by the state DS-Υ is mathematically defined as the event

$$\left\{ \bigcap_{j=1}^{n} X_j \le \overline{x}_j^{\Upsilon} \right\} \tag{7}$$

This event is defined as each EDP simultaneously *not* exceeding the prescribed limits set for DS-Υ. By considering all elements of $\mathbf{X}$ simultaneously not exceeding the associated threshold vector $\overline{\mathbf{x}}^{\Upsilon}$, the probability of this event can be expressed as

$$P\left[\bigcap_{j=1}^{n} X_j \le \overline{x}_j^{\Upsilon} \right] = \int_{-\infty}^{\overline{x}_n^{\Upsilon}} \cdots \int_{-\infty}^{\overline{x}_1^{\Upsilon}} f_{\mathbf{X}}(\mathbf{x})\, dx_1 \cdots dx_n = F_{\mathbf{X}}(\overline{\mathbf{x}}^{\Upsilon}) \tag{8}$$

The form of Equation (8) is sufficiently general to allow evaluation of the reliability of a particular structural system to meet some complex performance objective. This performance objective is termed "complex" because it need not be a single damage state limit for a single return period event. It is possible to specify *multiple* performance criteria, and subsequently assign a performance objective to *each* level of seismic hazard considered. In this case, the Seismic Performance Classification (SPC) is a function of simultaneously meeting each deterministic damage state limit at the level of hazard prescribed. Given the mathematical expression of Equation (7) that describes the event of meeting Damage State Υ for a seismic event having return period T_R, this notion of a multiple-objective SPC is defined as the simultaneous satisfaction (or nonexceedance) of k damage states at the corresponding k levels of seismic hazard, expressed as the event

$$\underbrace{\left\{ \bigcap_{j=1}^{n} X_j^{R_1} \le \overline{x}_j^{\Upsilon_1} \right\}}_{DS-\Upsilon_1|R_1} \bigcap \cdots \bigcap \underbrace{\left\{ \bigcap_{j=1}^{n} X_j^{R_k} \le \overline{x}_j^{\Upsilon_k} \right\}}_{DS-\Upsilon_k|R_k} \tag{9}$$

Note that each damage state need not be distinct, since the same damage limit could be targeted for multiple levels of hazard. Indeed, the same damage state could be targeted for *all* levels of seismic hazard and the SPC framework remains general. For example, the NEHRP Provisions (2003) states

> *Although the Provisions explicitly require design for only a single level of ground motion, it is expected that structures designed and constructed in accordance with these requirements will generally be able to meet a number of performance criteria, when subjected to earthquake ground motions of differing severity.*

The probability that a structure meets the designated SPC can be computed by recognizing that the demands resulting from seismic events having distinct frequencies of occurrence are largely independent, and therefore each of the three intersecting damage state events is assumed to be statistically independent of one another. Therefore, the probability of meeting an SPC is the product of the individual performance events, or

$$P\left[SPC\right] = F_{\mathbf{X}^{R_1}}(\bar{\mathbf{x}}^{\Upsilon_1}) \times \cdots \times F_{\mathbf{X}^{R_k}}(\bar{\mathbf{x}}^{\Upsilon_k}) \tag{10}$$

Application to Isolated Buildings

With the above definitions, it is possible to evaluate a wide class of isolation systems as to their ability to satisfy specified complex performance objectives. Recognizing the existence of potentially distinct limit state vectors for each performance classification, and an estimated mean vector $\hat{\mathbf{\Lambda}}$ and covariance matrix $\hat{\mathbf{\Psi}}$ for the lognormally-distributed demand vector $\mathbf{X}$ that depends on the earthquake intensity, a general statement of the probability that a structure meets Damage State Υ in an earthquake having return period T_R is given as

$$P_R^{\Upsilon} = F_{\mathbf{X}}(\ln \bar{\mathbf{x}}^{\Upsilon} \big| \hat{\mathbf{\Lambda}}^R, \hat{\mathbf{\Psi}}^R) \tag{11}$$

An SPC can be defined as an intersection of damage state non-exceedance events, shown in Equation (9). Table 3 describes the SPC designations defined for this study, approximately following the definitions of Seismic Use Group in NEHRP 2003. SPC-I corresponds to the intended performance classification of a typical facility. SPC-II is an enhanced performance classification. SPC-III is a safety-critical performance classification. SPC-IV is the highest performance classification considered. Additionally, demand limits are defined which follow the work of Aslani and Miranda (2006), which defined Damage States for generic components in terms of EDP limits. These are summarize below in Table 4, where DS1 through DS4 are assumed to correspond to F, IO, LS, and NC, respectively.

As an example of the trends in EDP's, the median demand hazard curves for the three-story isolated building analyzed are presented in Figure 2 for T_{eff} = 3 sec, ζ_{eff} = 0.25. In each plot, the median EDP (PIDR, PFA, or maximum isolator displacement) is plotted against its mean annual frequency (MAF) of occurrence. It is clear from the data presented that linear viscous and multi-stage isolators such as triple pendulum bearings show increased reliability in meeting seismic performance objectives in moderate and rare seismic events because of the lower median drift and acceleration demands relative to bilinear hysteretic isolation systems. This results from the known tendency for bilinear systems to exhibit large effective stiffness (and hence reduced effective isolation) at low levels of displacement (Fadi and Constantinou, 2009). For structures where reliable performance over a range of seismic hazard is desired, innovative devices should be considered and optimized depending on the specific performance objectives of the facility.

Given the estimation of all mean vectors $\mathbf{\Lambda}$ and covariance matrices $\mathbf{\Psi}$, and the defined limit state vectors $\bar{\mathbf{x}}$, the probability that an isolated building meets either SPC-I, II, III, or IV may be computed numerically following the procedure outlined. These results are presented in Table 5 for both three- and nine-story isolated buildings, including all targeted effective stiffness and damping parameters. This data is useful because it answers an important question posed in this paper: what is the probability that a facility satisfies the requirements for some target Seismic Performance Classification?

Table 3: Definition of Seismic Performance Classifications as a function of the collection of required damage state limits following corresponding seismic events of given return period

Seismic Event	T_R	SPC-I	SPC-II	SPC-III	SPC-IV
Frequent	72-yr	IO	F	F	F
Rare	475-yr	LS	IO	F	F
Very Rare	2475-yr	NC	LS	IO	F

Table 4: Statistical parameters for fragility functions of generic nonstructural drift-sensitive and acceleration-sensitive components (from Aslani and Miranda [2005])

	Peak Interstory Drift Ratio		Peak Floor Acceleration	
Damage State	Median (%)	Dispersion[1]	Median (g)	Dispersion[1]
DS1: Slight damage	0.4	0.5	0.25	0.6
DS2: Moderate damage	0.8	0.5	0.50	0.6
DS3: Extensive damage	2.5	0.5	1.00	0.6
DS4: Complete damage	5.0	0.5	2.00	0.6

[1] Defined as the logarithmic standard deviation of the demand

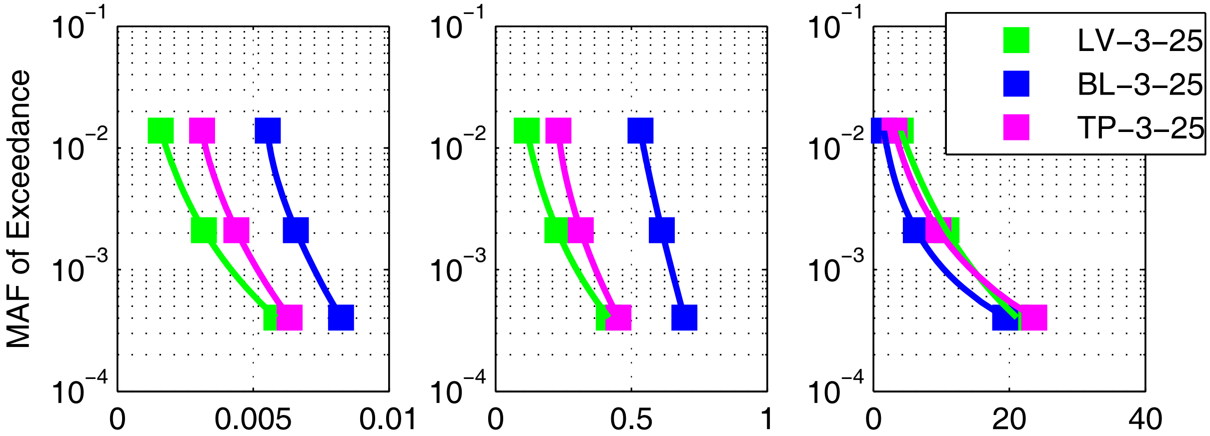

Figure 2: Median demand hazard curves for PIDR (left) PFA (center) and U_{iso} (right) for three-story isolated buildings on isolation systems having T_{eff} = 3 sec, ζ_{eff} = 0.25

Table 5: Probability of the three- and nine-story buildings satisfying each defined Seismic Performance Classification for all isolation systems considered ($P \geq 0.5$ shown bold.)

		3-Story Building				9-Story Building			
		Seismic Performance Class				Seismic Performance Class			
Isolation System		SPC-I	SPC-II	SPC-III	SPC-IV	SPC-I	SPC-II	SPC-III	SPC-IV
LV	3-10	**1.00**	**0.99**	0.44	0.05	**1.00**	**0.92**	0.12	0.00
	3-25	**1.00**	**0.97**	0.43	0.04	**0.99**	**0.80**	0.04	0.00
	4-10	**1.00**	**1.00**	**0.83**	0.25	**1.00**	**0.98**	**0.60**	0.05
	4-25	**1.00**	**0.99**	**0.72**	0.12	**1.00**	**0.91**	0.23	0.00
BL	3-10	**0.94**	0.04	0.00	0.00	0.44	0.01	0.00	0.00
	3-25	0.40	0.00	0.00	0.00	0.19	0.00	0.00	0.00
	4-10	**1.00**	**0.51**	0.10	0.01	**0.74**	0.04	0.00	0.00
	4-25	**0.90**	0.01	0.00	0.00	0.35	0.00	0.00	0.00
TP	3-10	**1.00**	**0.95**	0.38	0.07	**0.98**	**0.55**	0.01	0.00
	3-25	**1.00**	**0.59**	0.25	0.00	**0.86**	0.40	0.00	0.00
	4-10	**1.00**	**0.99**	**0.73**	0.47	**1.00**	**0.96**	**0.68**	0.14
	4-25	**1.00**	**0.91**	**0.57**	0.10	**0.94**	0.26	0.01	0.00

Conclusions

This paper highlight a well-known 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 target performance objectives implied in modern building code provisions.

To address this dilemma, a new class of isolation devices has been investigated. 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 hazard. The benefits of such devices is demonstrated in this study by looking at the trade-off between isolator displacement, peak inter-story drift, and peak floor accelerations. Whereas conventional bilinear hysteretic isolation bearings exhibit peak isolator displacements which are comparable to those observed for linear viscous and triple pendulum isolators, the peak drift and floor accelerations are comparatively excessive, especially for moderate levels of seismic excitation. The ability of multi-stage isolation systems to mitigate drift and acceleration demand is optimal behavior since the reliable performance of contents in a building is a concern for relatively frequent events, while stable performance of the isolation system is a consideration only in the very rare events. These results appear general for stiff and flexible superstructures, and for both long-period/high-damping and short-period/low-damping isolation systems.

To investigate the potential benefits of innovative isolation systems, a multi-objective Seismic Performance Classification (SPC) was introduced to describe aggregate damage state limitation over multiple levels of seismic hazard. From the analytical data presented in this paper, a probabilistic seismic demand analysis was performed to estimate the joint density functions of a vector of EDPs. Based on a series of limit state vectors assumed to describe discrete damage states, the probability of satisfying specific SPCs was computed for all isolated buildings investigated. The results demonstrate the importance of limiting inter-story drift and floor acceleration to satisfy complex seismic performance objectives, and the sensitivity of the performance reliability on the level and type of energy dissipation present.

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