Displacement-based risk-targeted design of base-isolated structures

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ABSTRACT: This paper discusses a risk-targeted displacement-based method to design and evaluate friction pendulum bearing (FPB) devices in base isolation systems. It is based on a simplified approach to quantify the mean annual frequency of exceeding a given device displacement threshold using basic FPB dimensions and properties. A case study example is discussed to illustrate its accuracy against more extensive assessments. Through such a method, it is envisaged that structural engineers can now quickly assess the actual failure rates of different FPB device combinations used in practice to obtain a more uniform level of safety or reliability. The proposed approach is also arguably simpler, more direct and more accurate than currently available code-based approaches in many regions.

1. INTRODUCTION

Base isolation gained popularity in the 1960s, with the first use on a school in Skopje. The 1980s saw the development of the friction pendulum bearing system (Zayas et al. 1990), which relies on friction and restoring force. These systems have since been applied to buildings, bridges, schools, and hospitals (Calvi and Calvi 2018).

Concerning seismic design provisions used to select and size base isolation devices, several codes of practice exist worldwide, such as Eurocode 8 (CEN 2004), ASCE/SEI 7-16 (2016), and NZSEE (2019). Guides to the Japanese code of practice are provided by Higashino and Okamoto (2006), among others. All methods and procedures for isolator device design generally follow the same trend: a trial selection of devices using equivalent linear models, followed by verification via dynamic analyses to check device performance (e.g., bearing displacement, uplift forces) and superstructure performance (e.g., story drift, floor acceleration) criteria. This often requires multiple design iterations.

Despite the perception of superior performance, base isolation systems have been critiqued for their relatively poor collapse performance in scenarios beyond what they were designed for, or when compared to other non-isolated systems (Iervolino et al. 2018). In the case of FPBs, this usually relates to the device reaching its maximum displacement capacity, or crashing into the moat wall, which can lead to failure of the device or a non-linear response from the superstructure. Hence, base isolation and FPB systems can provide excellent seismic protection for structures, yet the current design methods do not provide an effective and straightforward way to guarantee safety as defined by risk, and typically require a lot of trial and error when choosing devices.

This paper describes a displacement-based risk-targeted approach to sizing FPB systems for any type of structure. It takes advantage of the mechanical properties of FPB components and the closed-form risk solutions developed in recent years (Cornell and Krawinkler 2000).

2. OVERVIEW OF DESIGN APPROACH

This section outlines a displacement-based design approach for FPB-isolated systems targeting a specific level of acceptable risk. Section 2.1 first describes how seismic risk may be estimated in FPB system, and Section 2.2 describes how the required seismic fragility function may be estimated for FPB systems. Section 2.3 then combines these two to give a step-by-step description of the design approach.

2.1. Computing seismic risk

There are two important parts needed to estimate the risk: the seismic hazard at the site of interest and the seismic vulnerability of the structural system. The former involves a probabilistic seismic hazard analysis (PSHA), where the rate of exceeding a given level of intensity over a specified period may be computed. The second part represents the probability of exceeding a displacement threshold for a given intensity (i.e., seismic fragility function). These parameters, when combined, provide an indication of the likelihood that a certain displacement threshold will be exceeded. The mean annual frequency of exceedance (MAFE) for a chosen intensity measure (IM) can be calculated by combining the probability of failure, $P[\Delta>\Delta_{\text{lim}}|IM=im]$, with the site hazard curve, $H(im)$, in the following way:

$$\lambda_\Delta = \int_0^{+\infty} P[\Delta > \Delta_{lim}|IM = im]|dH(im)| \quad (1)$$

In the specific case of FPB-isolated systems, a site's hazard curve $H(im)$ can be computed for the IM = $Sa(T_{\text{iso}})$, where T_{iso} is the isolation period, $T_{iso} = 2\pi\sqrt{R/g}$, and R is the effective radius of curvature of the sliding surface. The probability of exceeding a displacement threshold limit in an FPB isolator system given an intensity of $Sa(T_{\text{iso}})$, $P[\Delta>\Delta_{\text{lim}}\ |IM = Sa(T_{\text{iso}})]$, is defined in Section 2.2.

Using the previously calibrated curves, a designer can calculate the risk of failure λ_Δ for a given isolator displacement, Δ, if the values of μ and R are known and the superstructure is expected to remain elastic. This can be used to identify device combinations of μ and R that satisfy a target MAFE and maximum displacement. For example, if a designer has limitations on the possible value of μ due to the sliding surface materials available to the device manufacturer, they can determine which value of R would meet the design requirements.

The MAFE can be estimated following the closed-form solution available in Vamvatsikos (2013) as:

$$\lambda_\Delta = \sqrt{p}k_0^{1-p}[H(im)]^p\, exp\left(0.5pk_1^2\beta_\rho^2\right) \quad (2)$$

$$p = \frac{1}{1+2k_2\beta_\rho^2} \quad (3)$$

$$H(im) = k_0 \exp\left(-k_1 \ln im - k_2 \ln^2 im\right) \quad (4)$$

where $H(im)$ represents the mean annual frequency of exceeding a ground shaking level of $Sa(T_{\text{iso}}) = im$, and can be quantified via the k_0, k_1 and k_2 fitting coefficients to the PSHA output. This essentially means if the hazard curve parameters are known, and the median seismic intensity required to exceed a displacement threshold limit is known along with its associated uncertainty, then the MAFE, or risk of failure, can be simply computed.

2.2. Estimating seismic fragility of FPB systems

To estimate the seismic fragility of FPB systems, O'Reilly et al. (2022) developed a simplified demand-intensity model for systems with the characteristic hysteretic behavior of FPB systems. First, the median intensity of the fragility function is given by:

$$Sa(T_{iso}) = \rho\mu \quad (5)$$

where μ is the friction coefficient of the sliding surface, and ρ is determined via the relationship calibrated by O'Reilly et al. (2022):

$$\rho = \left(\frac{\Delta}{\gamma}\right)^{1/\kappa} \tag{6}$$

where Δ is the displacement demand in the FPB isolation system, and the γ and κ terms are given by:

$$\gamma = 0.337\mu^{0.808}R^{1.02} \tag{7}$$

$$\kappa = 1.183R^{-0.088} \tag{8}$$

These equations can be used to determine the median $Sa(T_{\text{iso}})$ value of the fragility function at a given level of displacement demand, and the associated dispersion is given as:

$$\beta_\rho = 0.857\mu^{0.418}R^{0.403} \tag{9}$$

2.3. Step-by-step implementation

Following the description of the design approach, Figure 1 illustrates its step-by-step implementation.

3. CASE STUDY EXAMPLE

Using the displacement-based approach outlined in Figure 1, the seismic performance of an FPB isolation system may be evaluated via a case study example. It can be used quickly in design situations to test whether a particular isolation system is suitable before conducting a more thorough analysis.

For a building located in L'Aquila, Italy, the MAFE of exceeding an FPB displacement threshold of Δ_{lim} = 0.4m is determined for an FPB isolation system comprising μ = 3% and R = 4m isolators. This information encompasses Steps 1-3 outlined in Figure 1.

Step 4 is the identification of the seismic hazard. Since the isolator bearings are R = 4m and the ground motion IM is $Sa(T_{\text{iso}})$, the period of vibration was computed as T_{iso} = 4.01s. With T_{iso} known, the seismic hazard curve was identified (Step 5) for L'Aquila using the SHARE hazard model (Woessner et al. 2015) by performing a PSHA for $Sa(T_{\text{iso}}$=4.01s) using the OpenQuake engine, whose results are shown in Figure 2. Also shown are the hazard curves corresponding to other periods of vibration that may be investigated for other FPB isolator radii. Utilizing the second-order seismic hazard model fit, the coefficients for $Sa(T_{\text{iso}}$=4.01s) are k_0 = 8.18x10^{-7}, k_1=2.976 and k_2=0.186 (Step 5). Using the site hazard and candidate FPB isolator properties, the approach described previously was implemented to estimate the MAFE of the target displacement threshold of Δ_{lim} = 0.4m.

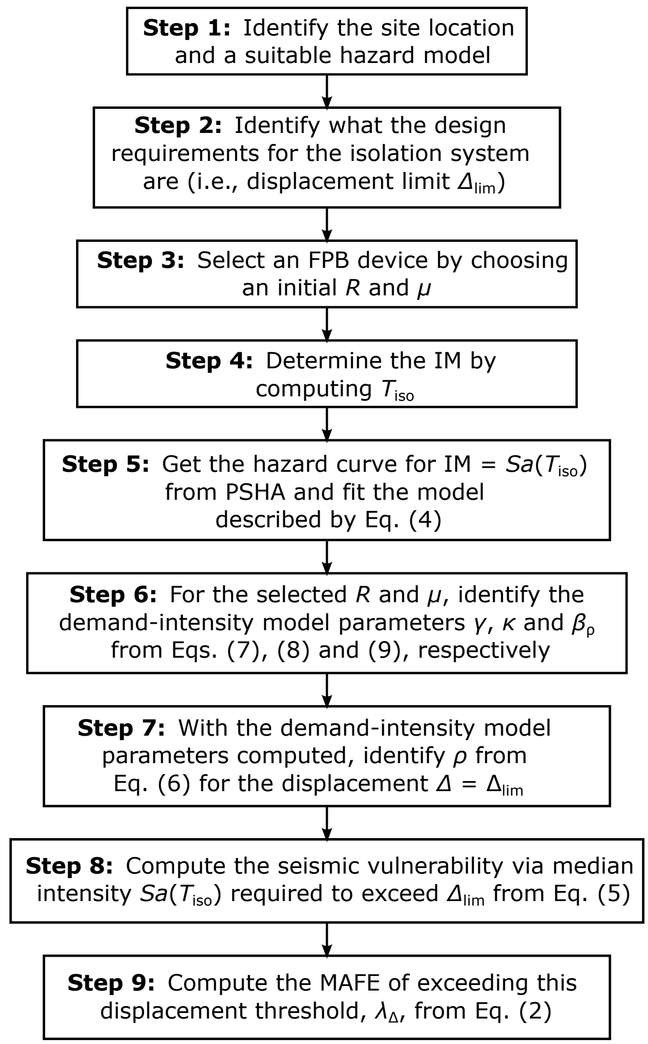

Figure 1: Step-by-step implementation of the proposed design procedure.

This value of MAFE for the given FPB isolator type and displacement threshold can be plotted as shown in Figure 3 via the red crosses. If the same exercise described above is repeated for many combinations of FPB isolator properties and displacement thresholds, the demand-hazard curves shown in Figure 3 can be generated quite easily. This would simply involve obtaining the site hazard curves corresponding to the different

FPB effective curvature radii, which were shown in Figure 2. Once obtained, the demand-hazard curves are easily computed by following the relatively simple calculations outlined. These were computed for a range of FPB isolator types and displacement threshold and are plotted in two different ways: Figure 3(top) highlights the impact on the MAFE for a given μ and different R values, whereas Figure 3(bottom) shows the impact of μ for a given value of R. It can be seen how in order to reduce the λ_Δ below a certain threshold, a designer would need to either decrease the R or increase the μ.

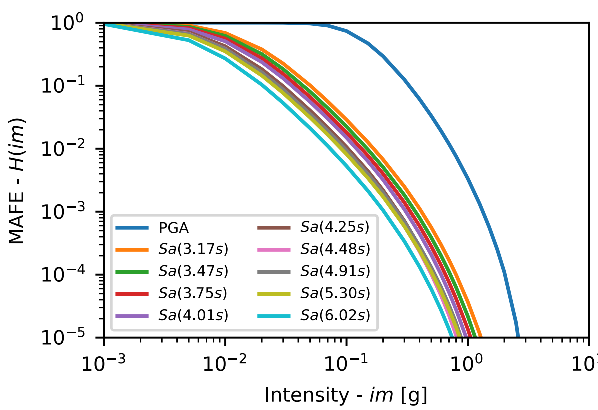

Figure 2: Mean hazard curves computed for a site in L'Aquila, Italy located at Longitude: 13.3995 Latitude: 42.3498 with a soil type of V_{s30} = 360m/s, corresponding to stiff soil.

By looking at the set of demand-hazard curves, a designer can assess the risk-based performance of any FPB isolation system. For example, for an FPB isolator with a displacement threshold of 0.4m, the MAFE is 1.895x10-4 which corresponds to a return period of 5276 years. This displacement threshold must not be exceeded in order to prevent collision or pounding, or damage to piping or other elements that bridge the isolation layer (as experienced during the Kumamoto and Tohoku earthquakes in Japan (Takayama 2016)). The designer can then verify whether this performance meets their requirements.

If a designer wants a displacement threshold of 0.3m and MAFE of 2475 years, Figure 3 indicates that only FPB isolators with R < 6m and μ > 3% would be suitable. However, due to potential non-linearity in the superstructure at these intensities, the assumption of an elastic superstructure must be verified. For a less stringent MAFE of 475 years, all isolation systems would meet the objectives for a 0.3m displacement threshold. On the other hand, for an MAFE of 5000 years and a 0.3m displacement threshold, Figure 3 indicates that none of the FPB isolators would be adequate and another supplemental system would be required.

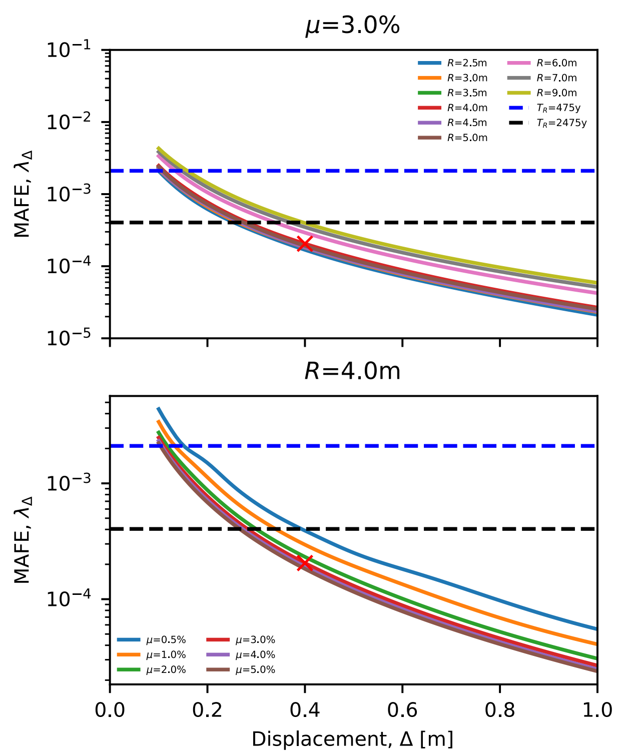

Figure 3: Demand-hazard curve for a range of FPB isolator combination types located in L'Aquila, Italy, where the curves (top) are for a fixed value of μ whereas (bottom) is for a fixed R.

4. DISCUSSION

The proposed procedure presented in this paper offers an effective and simple way to select FPB bearings for a risk-targeted seismic design of structures with isolators. The procedure does not provide a comprehensive method for isolated structures, but rather a dependable tool to quickly quantify and refine the risk of device failure, thus overcoming the limitations of the methods currently used in many building codes (ASCE 7-16 2016; CEN 2004; NZSEE 2019).

A comprehensive seismic design of buildings necessitates a dynamic verification analysis of the entire structure in order to ensure that other performance requirements (e.g. story drift or floor accelerations) are met. A solid starting design is always fundamental, especially with regard to the base shear and accelerations that are transmitted to the superstructure, which can be potentially problematic from both a structural and non-structural perspective (Shahnazaryan et al. 2022). These quantities can be adjusted by altering the properties of the device or the target device displacement limit.

It is important to note that past studies (Erduran et al. 2011; Kitayama and Constantinou 2019; Masroor and Mosqueda 2015; Pant and Wijeyewickrema 2014) have looked at potential structural collapse that occurs when a FPB device exceeds its displacement capacity or collides with the moat boundary wall. The design procedure proposed here is intended to provide risk mitigation against this type of problem. Other proposals (Kitayama and Constantinou 2018; Zayas et al. 2017) have suggested increasing the displacement capacity by a fixed ratio without full consideration of seismic hazard uncertainty (Baker et al. 2021), which may not be the most effective risk mitigation strategy, which has also been advocated by recent work by Kazantzi and Vamvatsikos (2020).

5. SUMMARY

In this paper, a displacement-based design methodology for single friction pendulum bearing (FPB) isolation systems targeting an acceptable risk was presented. This approach utilizes a closed-form and simplified probabilistic approach to assess the risk of failure from the device displacement response, knowing only the site seismic hazard and the FPB device properties (i.e., dynamic friction coefficient and effective radius of curvature). This is in comparison to current design methods offered in building codes around the world which focus on a trial-and-error intensity-based approach. The detailed risk-based methodology was presented step-by-step with examples to facilitate its practical application. A set of case studies were used to measure the risk of failure based on displacement for each structure. Through this design approach, the following points can be noted:

- This method provides designers with an easier way of sizing and selecting their FPB isolation systems based on their risk assessment. It is simpler than current design methods used in building codes, which often involve trial and error processes after numerical verification analyses. Implementing this method requires just a few simple steps and gives designers a better starting point before conducting their verification analyses.
- By having knowledge of the FPB isolation system (without the need for any numerical analysis) and knowing the displacement threshold, the risk of device failure in existing buildings in a given region can be quickly estimated, allowing us to identify the isolated structures at an unacceptably high level of risk. This is a powerful tool when it comes to the regional assessment of such building typologies.
- We have not taken into account other sources of device uncertainty in this study, such as velocity or heating effects and the influence of higher mode contribution from a superstructure. Further research is needed to gain more insight into these aspects and to provide design guidance on how to incorporate them into a simplified tool.
- Further research should be conducted to determine the effects of overall building performance on the context discussed. This would include exploring the flexibility of the superstructure, any potential non-linear behavior, and the economic losses that may occur due to a collision between the moat wall or isolator

boundary. This study applies to lower to mid-rise structures, where the first mode response is prominent; however, its application to taller buildings, where the first mode response is not as significant, should also be examined.

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