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Seismic reliability of base-isolated structures with friction pendulum bearings

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ABSTRACT

The friction pendulum system (FPS) is becoming a widely used technique for seismic protection and retrofit of buildings, bridges and industrial structures due to its remarkable features such as the stability of physical properties and durability respect to the elastomeric bearings. Experimental data also showed that the coefficient of friction depends on several effects (i.e., sliding velocity, apparent pressure, air temperature, cycling effect) so that it can be assumed as a random variable. The aim of the study consists in evaluating the seismic reliability of a base-isolated structure with FP isolators considering both isolator properties (i.e., coefficient of friction) and earthquake main characteristics as random variables. Assuming appropriate density probability functions for each random variable and adopting the Latin Hypercube Sampling (LHS) method for random sampling, the input data set has been defined. Several 3D non-linear dynamic analyses have been performed considering both the vertical and horizontal components of each seismic excitation in order to evaluate the system response. In particular, monovariate and multivariate (joint) probability density and cumulative distribution functions have been computed and, considering the limit state thresholds and domains (performance objectives) defined respectively on mono/bi-directional displacements, assumed as earthquake damage parameter (EDP) according to performance-based seismic design, the exceeding probabilities (structural performances) have been evaluated. Estimating the reliability of the superstructure, substructure and isolation level led to define and propose reliability-based abacus and equations useful to design the FP system.

1. Introduction

The friction pendulum system (FPS) is becoming a widely used technique for seismic protection and retrofit of buildings, bridges, and industrial structures due to its remarkable features such as the stability of physical properties and durability respect to the elastomeric bearings [1,2]. Moreover, other advantages are the separation between the restoring and dissipating action, the better control of the fundamental vibration period, the large deformation capacity by using simple geometric forms and the reduced torsional effects, since the frictional forces developed by the bearings are proportional to the mass directly supported [3,4].

Within the issue of controllable seismic isolation systems, studies are usually developed through deterministic analyses in which the isolation system characteristics, structural system properties, earthquake characteristics, and device properties are not random variables and the inherent uncertainties in these systems are not taken into account.

Over the years, probabilistic analyses in structural dynamics, structural reliability methods, and reliability-based analysis [5,6] are also contributing to the development of the field by evaluating the stochastic responses of base-isolated structures under random earthquake excitations. Reliability evaluation of base-isolated systems has been presented by Chen et al. [7], as well as Monte Carlo simulations have been performed by Fan and Ahmadi [8] and Su and Ahmadi [9] to analyze the stochastic response of sliding isolation systems under random earthquake excitations. Many studies have also been focused on reliability analysis and reliability-based optimization of base-isolated systems including uncertainties such as isolation device properties and ground motion characteristics [10–13].

With reference to isolated systems with FP bearings, the inherent uncertainties of the sliding coefficient of friction at different velocities, overall structural properties and earthquake characteristics can affect the dynamic response and, therefore, the above-mentioned uncertainties should be considered in the dynamical analyses using random variables.

The aim of the study consists in evaluating the seismic reliability of an ordinary 3D base-isolated structure through FP isolators with a design life of 50 years and located near L'Aquila site

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Nomenclature

a	sliding velocity transition rate parameter of the FPS	u	horizontal displacement of the FPS
$\mathbf{C}$	damping matrix of the base-isolated building	$\dot{u}$	sliding velocity of the FPS
F	FPS restoring force	U_m	random number generated between 0 and 1
F_a	FPS resultant friction force	u_x	absolute maximum horizontal relative displacement along x direction of the FPS
$f_{\max}$	sliding coefficients of friction at large velocity of the FPS	u_y	absolute maximum horizontal relative displacement along y direction of the FPS
$f_{\min}$	sliding coefficients of friction nearly zero velocity of the FPS	W	weight on the bearing
F_Y^{-1}	inverse cumulative distribution function	W_s	total weight of superstructure and isolation level
g	gravity acceleration	w_s	uniformly distributed seismic weight
$\mathbf{K}$	stiffness matrix of the base-isolated building	Y_i	i-th random variable
K_1	FPS elastic stiffness	$Y_{i,j}$	j-th sample value of the i-th random variable
K_2	FPS post elastic stiffness	α	mass proportional coefficient related to Rayleigh damping
$\mathbf{M}$	mass matrix of the base-isolated building	β	reliability index
M	mass on the bearing	β	stiffness proportional coefficient related to Rayleigh damping
m	integer counter between 1 and j	δ_x	absolute maximum interstory drift along x direction
M	magnitude	δ_y	absolute maximum interstory drift along y direction
P_f	exceeding probability	Θ	rotational degree of freedom of the 3D building around vertical axis
$p_{i,j}$	cumulative probabilities of the random variables	μ	sliding coefficient of friction of the FPS
Q_d	FPS characteristic strength	$\mu_{\ln(\delta)}$	mean of $\ln(\delta)$
r	radius in plan of the FPS	ξ_{is}	dimensionless damping coefficient of the base-isolated building
R	radius of curvature of the FPS	ρ	correlation coefficient
R	epicentral distance	$\sigma_{\ln(\delta)}$	standard deviation of $\ln(\delta)$
S	resultant force of normal pressure of the FPS		
S_a	elastic pseudo-acceleration		
sgn	signum function of the sliding velocity		
T	first natural period of the fixed-base structure		
T_{is}	fundamental period of vibration of the base-isolated system		

(Italy), considering both earthquake main characteristics (i.e., spectral response acceleration at isolated structural period) and isolator properties (i.e., sliding coefficient of friction) as random variables by performing several non-linear dynamic analyses with the three ground motion components [3]. In particular, normal and uniform probability density functions (PDFs) have been assumed according, respectively, to seismic hazard of the specific site as provided by NTC08 [14] and experimental tests on FPS [15–17]. Adopting the Latin Hypercube Sampling method (LHS) [18–21] as random sampling technique, the input data set has been defined to perform 3D non-linear dynamic analyses.

Monovariate and multivariate probability density and cumulative distribution functions have been computed and, considering both limit state thresholds and domains (performance objectives “PO”), defined respectively on mono/bi-directional displacements, assumed as earthquake damage parameter (EDP) according to performance-based seismic design [22], the monovariate and bivariate exceeding probabilities (structural performances “SP”) have been evaluated.

The reliability evaluation related to the superstructure, substructure and isolation level allowed to define and propose reliability-based abacus and equations useful to design the FP system.

Finally, a comparison between the results, achieved by assuming the above-mentioned PDFs, and those obtained following the PEER-like modular approach [23], usually employed in seismic risk and reliability analyses, is discussed to validate the effectiveness of the structural reliability curves as well as the proposed reliability-based abacus and derived equations useful to design FP bearing devices.

2. Seismic reliability and performance objectives

Seismic reliability assessment of a building structure, according to the structural performance evaluation method [24–26], is based on the coupling between structural performance levels [22] and associated reliability indices β or exceeding probabilities during its design life [27,28].

As for performance levels of a building, four discrete performance levels or limit states (*LS1, LS2, LS3, LS4*), corresponding respectively to “fully operational”, “operational”, “life safety” and “collapse prevention” are provided by Vision 2000 [22]. Within the displacement-based seismic design, each one of the performance item has been defined in terms of measurable structural response parameter IDI, Interstory Drift Index, [25] and related to an acceptable probability of going beyond that limit state, or failure probability, in the design life of a structure [24–26].

In Table 1, with reference to a fixed-base reinforced concrete structure, the limit states as well as the values of both failure probabilities and reliability indices β in 50 years are reported as provided by [27,28]. In Fig. 1, the corresponding “performance curve” is illustrated.

In the “performance space” [24,25] (Fig. 1), three performance curves are here represented. Starting from the performance levels previously identified, related to fixed-base systems, the performance limit states for base-isolated buildings, in accordance to

Table 1
Limit states corresponding to interstory drift indices and reliability indices in 50 years [24–26].

Performance of building	Limit state	Interstory drift index (%)	Reliability index β	P_f
Concrete crack	LS1	0.30	0	$5.0 \cdot 10^{-1}$
Damage on secondary elements	LS2	0.60	1	$1.6 \cdot 10^{-1}$
Failure of structural elements	LS3	1.50	2	$2.2 \cdot 10^{-2}$
Collapse of building	LS4	2.00	3	$1.5 \cdot 10^{-3}$