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Seismic reliability-based robustness assessment of three-dimensional reinforced concrete systems equipped with single-concave sliding devices

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ABSTRACT

The aim of the study consists of evaluating the seismic robustness of a three-dimensional (3D) reinforced concrete (r.c.) structure equipped with single-concave friction pendulum system (FPS) devices by estimating the seismic reliability in its design life (50 years) of different models related to different malfunction scenarios of the seismic isolators. Among the uncertainties, the elastic response pseudo-acceleration corresponding to the isolated period is assumed as the relevant random variable and, by means of the Latin Hypercube Sampling technique, the input data have been defined in order to develop 3D inelastic time-history analyses. In this way, bivariate structural performance curves at each level of the r.c. structural system as well as seismic reliability-based design abacuses for the FP devices have been computed and compared to evaluate the robustness of the r.c. system considering different models related to the different failure scenarios analysed. Contextually, the seismic robustness of the abovementioned r.c. structural system has also been examined by considering both a configuration equipped with beams connecting the substructure columns and a configuration without these connecting beams in order to demonstrate their effectiveness in improving the seismic robustness in the scenario of a malfunction of a seismic device and provide very useful design recommendations for base-isolated structures equipped with FPS.

1. Introduction

In these last decades, seismic isolation through friction pendulum system (FPS) devices has become increasingly an effective technique for the protection of structures and infrastructure [1,2]. Over the years, robustness and probabilistic analyses, structural reliability methods and reliability-based analysis [3,4] by estimating the stochastic responses of base-isolated systems as well as the stochastic responses of sliding isolation systems [5,6] have been analysed under random earthquake excitations. The use of a robust control in conjunction with base isolation in order to assure arbitrarily small motion of a seismically excited structure has been proposed by [7]. Other studies have presented reliability analysis and reliability-based optimization of base-isolated structures including uncertainties such as isolator properties and ground motion characteristics [8–11]. A nondimensionalization of the motion equations for a two-degree-of-freedom model considering the superstructure flexibility and a velocity-dependent response for the FPS device behavior has been proposed by [12].

Considering both the bearing properties [13] and earthquake main characteristics as random variables, seismic reliability analyses of a three-dimensional (3D) reinforced concrete (r.c.) system isolated by FPS isolators with a lifetime of 50 years and located near L'Aquila site (Italy) have been performed in Palazzo et al. [14] and Castaldo et al. [15]. These recent literature studies have highlighted that the bivariate correlation between the response parameters influences the structural performance (SP) curves and proposed a method for the design of the isolator dimensions in plan. In [16], the life-cycle cost analysis (LCCA) of a 3D r.c. system isolated by FP devices is discussed describing the positive benefits derived from increasing values of the isolation degree. For different structural properties, the seismic reliability-based design approach (SRBD) has been proposed in [17] as a new methodology aimed at providing useful design solutions for the seismic devices. A recent work of [18] has evaluated the optimal friction of FP isolators for three different sets of artificial records representative of different soil conditions highlighting that higher friction coefficients are required for soft soil condition to minimize the superstructure response. In [19], the optimal values of the friction coefficient taking into account the influence of the ground motion characteristics by means of the ratio PGV/PGV have been proposed. The seismic performance of bridges isolated with FPS considering different limit states has been

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Table 1
Limit states in terms of maximum Interstory Drift Indices (IDI) and reliability indices in 50 years for fixed-base and base-isolated systems [21,39,40].

Limit state	Damage	FB structure IDI (%)	Reliability index β	P_f	BI structure IDI (%) (NTC 08)	BI structure IDI (%) (FEMA-274)
LS1	Slight	0 < IDI < 0.3	0	$5.0 \cdot 10^{-1}$	0 < IDI < 0.2	0 < IDI < 0.1
LS2	Moderate	0.3 < IDI < 0.6	1	$1.6 < 10^{-1}$	0.2 < IDI < 0.4	0.1 < IDI < 0.2
LS3	Heavy	0.6 < IDI < 1.5	2	$2.2 < 10^{-2}$	0.4 < IDI < 1.0	0.2 < IDI < 0.5
LS4	Collapsed	IDI > 2	3	$1.5 < 10^{-3}$	IDI > 1.3	IDI > 0.7

investigated in [20]. Seismic reliability-based relationships between the strength reduction factors and the displacement ductility demand for base-isolated systems, characterised by an equivalent perfectly elastoplatic behavior and equipped with FP devices, have been proposed by [21]. In [22], the robustness of base-isolated high-rise buildings with friction-type bearings has been evaluated leading to the conclusion that base-isolated low-rise buildings have a higher robustness than base-isolated high-rise buildings. In addition, an approach for a robust design optimization of base isolation system considering random system parameters related, respectively, to the structure, isolator and ground motion model has been performed in [23] by minimizing the weighted sum of the both statistical parameters of the maximum root mean square acceleration of the structure.

The abovementioned studies have dealt with the robustness of base-isolated systems focusing always on the effectiveness of the design approaches without examining the structural response in the scenario of a malfunction of a passive device with the possible design solutions. For this purpose, this work proposes an important robustness requirement for systems equipped with supplemental control devices: the robustness analysis should also be focused on the failure scenarios of the control system. With reference to seismic isolation through PFS devices, the failure scenarios as well as the design solutions are herein widely discussed in reliability terms. In fact, this study aims at evaluating the seismic robustness of a 3D r.c. base-isolated structure equipped with single-concave friction pendulum system (FPS) devices, designed according to NTC08 [24] and also analysed in Castaldo et al. [15,16], by estimating the seismic reliability in the design life (50 years) of different models related to different malfunction scenarios of the seismic isolators. Specifically, among the uncertainties, the elastic response pseudo-acceleration corresponding to the isolated period is assumed as the relevant random variable, modelled through a Gaussian probability density function (PDF) [24], and, by means of the Latin Hypercube Sampling (LHS) technique [28–31], the input data have been defined for each model. After that, 3D inelastic time-history analyses have been developed taking into account both the three components of each seismic ground motion and the inelastic response of the whole system. In this way, bivariate structural performance (SP) curves at each level of the r.c. structure as well as seismic reliability-based design (SRBD) abacuses for the FP bearings have been computed and compared to evaluate the robustness of the system within the different failure scenarios considered. Moreover, the seismic robustness of the abovementioned r.c. structure has also been examined by considering both a configuration equipped with r.c. beams connecting the substructure columns and a configuration without these connecting beams to demonstrate their effectiveness in reducing a damage level disproportionate to the original cause and, therefore, improving the seismic robustness, especially, of the substructure for a malfunction of a seismic device. The main results of this study can represent very useful design recommendations for base-isolated structures equipped with FPS isolators.

2. Seismic robustness analysis: structural system, failure scenarios and uncertainties

The seismic robustness assessment of the base-isolated r.c. structure, developed in probabilistic terms in this study as discussed in the following, requires the seismic reliability analysis of the different models representative of the different failure scenarios of the seismic devices herein assumed.

For the seismic reliability evaluation, according to the several guideline documents, code provisions and literature studies [32–38], relationships between the four structural performance objective (PO) levels, expressed for example in terms of the maximum interstory drift limits for each limit state (*LS*), and the corresponding reliability indices β, or probabilities exceeding the *LS* thresholds during the lifetime of the structural system [33], have been established. Specifically, with reference to both a fixed-base (FB) and base-isolated (BI) moment frame ordinary r.c. structure with moderate consequences of structural failure, these abovementioned correlations are presented in Table 1 according to both FEMA-274 [34] and the Italian seismic code [24] provisions, respectively, and illustrated as PO curves in the performance space [38] of Fig. 1. The assessment of the seismic reliability of a BI structure, therefore, consists of computing and comparing the structural performance (SP) curves to the corresponding PO curves provided by the codes [14–17].

For the seismic robustness assessment, the damage levels consequential to the failure scenarios are estimated in the performance space in probabilistic terms by means of the SP curves representing the probabilities exceeding the extreme values of the engineering demand parameters (EDPs), assumed as, respectively, mono/bi-variate interstory drift (ID) δ for the sub/super-structure and mono/bi-variate relative displacement u for the FP devices. It follows that the exceeding probability is, herein, assumed as the measure of the seismic robustness and, therefore, a reduction in terms of seismic reliability represents also a decrease of the seismic robustness. In this work, two structural configurations (with and without the connecting beams at the substructure level) are also considered in order to estimate the ability of the connecting beams at the substructure level to avoid or reduce a damage level disproportionate to the original cause (failure of a seismic device), so, their contribution to increase the seismic robustness, especially, of the substructure.

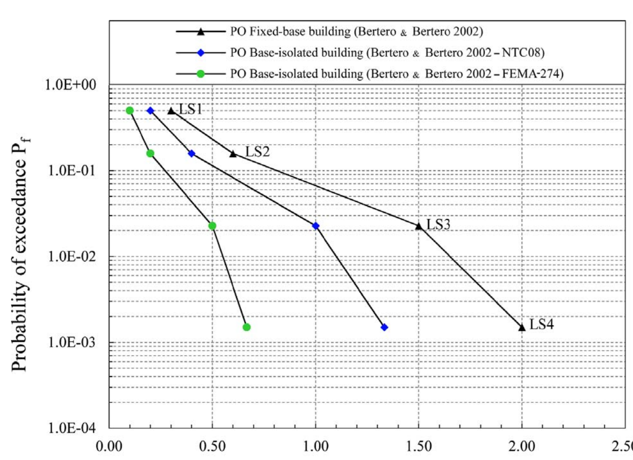

Fig. 1. Probabilities of exceedance (in 50 years) related to the four limit state thresholds for fixed-base and base-isolated systems in the "performance space" [38].