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Lateral-torsional response of base-isolated buildings with curved surface sliding system subjected to near-fault earthquakes

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ABSTRACT

The curved surface sliding (CSS) system is one of the most in-demand techniques for the seismic isolation of buildings; yet there are still important aspects of its behaviour that need further attention. The CSS system presents variation of friction coefficient, depending on the sliding velocity of the CSS bearings, while friction force and lateral stiffness during the sliding phase are proportional to the axial load. Lateral-torsional response needs to be better understood for base-isolated structures located in near-fault areas, where fling-step and forward-directivity effects can produce long-period (horizontal) velocity pulses. To analyse these aspects, a six-storey reinforced concrete (r.c.) office framed building, with an L-shaped plan and setbacks in elevation, is designed assuming three values of the radius of curvature for the CSS system. Seven in-plan distributions of dynamic-fast friction coefficient for the CSS bearings, ranging from a constant value for all isolators to a different value for each, are considered in the case of low- and medium-type friction properties. The seismic analysis of the test structures is carried out considering an elastic-linear behaviour of the superstructure, while a nonlinear force-displacement law of the CSS bearings is considered in the horizontal direction, depending on sliding velocity and axial load. Given the lack of knowledge of the horizontal direction at which near-fault ground motions occur, the maximum torsional effects and residual displacements are evaluated with reference to different incidence angles, while the orientation of the strongest observed pulses is considered to obtain average values.

1. Introduction

Base-isolation by means of friction bearings has proved to be highly effective for the seismic protection of buildings and bridges, as it ensures a considerable reduction of the horizontal ground acceleration transmitted to the superstructure through the limitation of the friction force [1]. The simplest friction isolator is the flat surface sliding (FSS) bearing, which is insensitive to the frequency of the seismic input but lacks any re-centring capacity [2]. To overcome this problem, a FSS bearing can be combined in series (e.g. the Electricité-de-France, EDF) or in parallel (e.g. the Resilient-friction base isolator, R-FBI) with an elastomeric bearing acting as restoring force device [3–5]. However, both systems can need re-centring

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after an earthquake to ensure that the restoring force of the elastomeric bearing has not exceeded the friction threshold of the sliding plates [6].

The curved surface sliding (CSS) system, on the other hand, consists of a spherical concave sliding surface where the geometry and gravity allow a minimization of torsion and a self-centring of the base-isolation system for a wide range of frequency inputs [7,2,8,9]. Recently, double and triple CSS bearings, with different radii of curvature and friction coefficients, have been proposed [10,11], accommodating larger horizontal displacements than the single CSS bearing. Many alternative formulations have been proposed to attenuate the low-frequency resonance of the single CSS bearings, shifting the fundamental vibration period of the base-isolated structure away from the predominant period of the ground motion: e.g. variable CSS bearing, where the friction coefficient is varied along the sliding surface by an exponential law [12,13]; single and double variable CSS bearings, where the radius of curvature is lengthened with an increase of the isolator displacement [14,15]; variable frequency CSS bearing, with an elliptical sliding surface to achieve a progressive vibration period shift at different response levels [16].

In spite avant-garde sliding bearings have been proposed, the application of the single CSS system is growing due to its conceptual simplicity, but there are still aspects of its behaviour that need further attention [17]. During the sliding phase tends to be a coincidence between the centre of stiffness of the CSS system, proportional to the axial load on the CSS bearings, and the centre of mass of the superstructure. However, the sliding velocity affects the friction coefficient, with an increase of sliding velocity up to a constant value [18]. Moreover, the friction coefficient is inversely proportional to the axial load, with a high-velocity (dynamic-fast) value significantly varying with the axial load and a low-velocity (dynamic-low) value which is relatively unaffected [19]. In practice, the axial load changes continuously during an earthquake and high values of the sliding velocity are expected under the horizontal components of near-fault ground motions, which are characterized by fling-step and forward-directivity effects with strong long-duration velocity pulses [20,21]. Thus, torsional effects and residual displacements may happen for base-isolated structures with single CSS bearings located in near-fault areas. However, the main conclusion of some studies is that coupled lateral-torsional response is negligible in sliding isolated structures subjected to far-fault ground motions, even in the presence of large mass and stiffness eccentricities [22–24]. On the other hand, other studies highlight that lateral-torsional coupling can be significant depending on the superstructure eccentricity and the lateral-torsional flexibility of both superstructure and base-isolation system [25].

To analyse lateral-torsional response of base-isolated structures with single CSS bearings subjected to horizontal components of near-fault ground motions, a six-storey reinforced concrete (r.c.) office building, with an L-shaped plan and setbacks at different heights along the in-plan X (i.e. one setback, at the third-storey) and Y (i.e. two setbacks, at the second- and fourth-storey) principal directions, is designed in line with the Italian seismic code [26]. The study presents a parametric investigation in which asymmetries in both the superstructure, with constant eccentricity between stiffness and mass centres due to in-plan and in-elevation irregularities, and CSS base-isolation system, with variable eccentricities between the centres of mass and strength corresponding to different positions of the application point of the resultant of friction forces in the CSS bearings, are considered. To this end, three values of the radius of curvature for the single CSS bearings are considered in the case of low- and medium-type friction. Moreover, seven in-plan distributions of the dynamic-fast friction coefficient are examined for the single CSS bearings, ranging from a constant value for all isolators to a different value for each. The paper is focused on peak response parameters for the CSS base-isolation system, assuming a strength of the superstructure so high that an operational performance level of the r.c. frame members is achieved even under strong earthquakes. This assumption is in agreement with the aseismic design philosophy commonly adopted for base-isolated structures where a behaviour factor equal to one is considered in order to exclude plastic deformations in the superstructure under strong earthquakes. Specifically, the nonlinear seismic analysis is carried out hypothesizing an elastic behaviour of the superstructure and a nonlinear force-displacement law for the single CSS bearings, depending on sliding velocity and axial load. Seven near-fault ground motions available in the *Pacific Earthquake Engineering Research centre database* (PEER, 2008, [27]) are selected in accordance with the design hypotheses adopted for the test structure (i.e. high-risk seismic region and soil-site) also taking into account the orientation of the strongest observed pulses, available in an online database of pulse-like ground motions [28]. Then, maximum torsional effects and residual displacements are evaluated considering a series of time histories for different incidence angles of the horizontal components of ground acceleration, increased in the range 0–360° with a constant step of 30°, while the orientation of the strongest observed pulses is assumed to obtain average effects.

2. Modelling and analysis of the base-isolated structure with curved surface sliding system

The CSS bearing consists of a spherical concave sliding surface with equivalent downward (Fig. 1a) or upward position [29]; it has a radius of curvature R and a centre of curvature C (Fig. 1b), and an articulated slider with a dynamic friction coefficient μ. The friction coefficient is usually prescribed as a function of several factors [30], the most influential being velocity and axial load. During the sliding phase, the slider moves on the spherical surface thereby dissipating energy by friction, while the superstructure translates horizontally ($\boldsymbol{u}_H$) and lifts vertically (u_V). The friction force for bidirectional motion with velocity vector $\dot{\boldsymbol{u}}_H$ is equal to [31,32]

$$\boldsymbol{F}_f = \begin{Bmatrix} F_{f,x} \\ F_{f,y} \end{Bmatrix} = \mu F_c \frac{1}{\|\dot{\boldsymbol{u}}_H\|} \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} \cong \mu N \frac{1}{\|\dot{\boldsymbol{u}}_H\|} \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} \quad (1)$$