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Sensitivity to modelling and design of curved surface sliding bearings in the nonlinear seismic analysis of base-isolated r.c. framed buildings

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ABSTRACT

The main object of this study is to investigate the influence that different modelling assumptions of the curved surface sliding (CSS) bearings may have on the lateral-torsional response of irregular base-isolated structures located in near-fault area, characterized by fling-step and directivity effects with large amplitudes and long period horizontal velocity pulses. The second aim is to evaluate the effects of different design assumptions of the CSS system. To this end, a six-storey base-isolated reinforced concrete (r.c.) framed building, with an L-shaped plan and setbacks in elevation, is designed assuming low- and medium-type friction properties, both with two in-plan distributions of the dynamic-fast friction coefficient, corresponding to: (i) the same value for all isolators; (ii) a different value for each isolator. Four additional cases are compared reducing the friction coefficient in accordance with a temperature increase up to 250 °C during ground motions. A computer code for the nonlinear dynamic analysis is developed, in order to compare five models of the CSS bearings that consider constant and variable axial loads combined with constant and variable friction coefficients as function of sliding velocity, axial pressure and stick-slip effect. A lumped plasticity model is used to describe the inelastic behaviour of the superstructure, including a 26-flat surface modelling of the axial load-biaxial bending moment elastic domain at the end sections of r.c. frame members. Near-fault ground motions with significant horizontal components are selected and scaled in line with the design hypotheses adopted for the test structure.

1. Introduction

The application of the curved surface sliding (CSS) bearings is found to be most attractive due to its conceptual simplicity [1], even if there are important aspects that require further attention. The main advantages of CSS bearings in comparison with other base-isolation systems are the minimization of torsional effects and residual displacements. Indeed, mass irregularities of the superstructure are balanced by spatial variation in the horizontal stiffness of the CSS bearings, proportional to the axial load during the sliding phase, which are able to recenter due to their concave sliding surface. However, the constant fundamental vibration period of the CSS system can become critical for base-isolated structures subjected to large pulse-like earthquakes generated at near-fault sites, inducing resonance, if it is close to the predominant vibration period of the ground motion [2–4], and torsional coupling, in asymmetric base-isolated buildings [5,6]. The increase in the friction coefficient at the sliding surface of the CSS bearings is an appropriate means of controlling the isolator displacement, thereby obviating the use of large isolators [7], but it can induce re-centring problems [8,9] and it does not guarantee a better performance of the superstructure in terms of structural and non-structural damage [10]. Avant-garde CSS bearings with double and triple independent sliding surfaces [11,12], whose different radii of curvature and friction coefficients are easily adaptable to variable seismic intensity levels, can deal with larger horizontal displacements better than the CSS bearing. Moreover, to attenuate the low-frequency resonance of the CSS bearings many alternative formulations have been proposed, shifting the fundamental vibration period of the base-isolated structure away from the predominant period of the ground motion [13–16].

Current international seismic codes [17] and guidelines [18] allow for the use of simple bilinear curves to describe the nonlinear response of the CSS bearings, in order to reduce the computational effort for the nonlinear dynamic analyses. However, theoretical and experimental studies have uncovered the complex nonlinear behaviour of the CSS bearings, highlighting the presence of many parameters affecting their friction coefficient at the sliding surface. The friction force changes with: (a) the sliding velocity, whose increasing values produce a friction coefficient which increases by an exponential law [19]; (b) the axial pressure, with a high-velocity (dynamic-fast) value of the friction coefficient significantly reducing with the axial pressure and a low-velocity (dynamic-low) value which is relatively unaffected [20,21]; (c) the temperature when the slider is in motion, influencing the friction

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coefficient which decreases rapidly as the temperature at the sliding interface increases from −40 °C to 20 °C and tends to a constant value for temperatures greater than 250 °C [22]; (d) the stick-slip phases, producing a transition between static and kinetic friction coefficients whose ratio varies between 1.5 and 4.5 depending on the friction material adopted to coat the slider [23]. Moreover, the axial load changes during an earthquake, producing variations proportional to its current value for both the friction force and lateral stiffness during the sliding phase.

These considerations show the need for a suitable numerical model to describe the nonlinear behaviour of a CSS bearing. To this end, 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 [24]. Low- and medium-type friction properties with two in-plan distributions of the dynamic-fast friction coefficient are considered, assuming: (i) the same value for all isolators; (ii) a different value for each isolator. Moreover, four additional design cases are compared by reducing the friction coefficient in accordance with a temperature increase up to 250 °C during ground motions. A computer code for the nonlinear dynamic analysis is developed, in order to compare eight structural solutions through five models of the CSS bearings that consider: i) constant axial load and constant friction coefficient (CALCFC model); ii) constant axial load and variable friction coefficient with velocity (CALVFC1 model); iii) variable axial load and variable friction coefficient with velocity (VALVFC1 model); iv) variable axial load and variable friction coefficient with velocity and pressure (VALVFC2 model); v) variable axial load and variable friction coefficient with velocity, pressure and stick-slip effect (VALVFC3 model). A lumped plasticity model describes the inelastic behaviour of the superstructure, including a 26-flat surface modelling of the axial load-biaxial bending moment elastic domain at the end sections of r.c. frame members. Seven near-fault ground motions are selected from the *Pacific Earthquake Engineering Research center database* [25] and normalized in accordance with the design hypotheses adopted for the test structure (i.e. high-risk seismic region and soil-site).

2. Modelling of the curved surface sliding system

The CSS bearing consists of a spherical concave sliding surface, with a radius of curvature R (Fig. 1a), and an articulated slider, with contact surface S and friction coefficient μ. During the sliding phase, the slider moves on the spherical surface thereby dissipating energy by friction, while the superstructure translates horizontally ($\boldsymbol{u}_H$). For bidirectional motion (Fig. 1b) with velocity vector $\dot{\boldsymbol{u}}_H$, the restoring force during the sliding phase ($\boldsymbol{F}_H$) contains pendular and friction components that can be evaluated by the rotational equilibrium equation around the center of curvature C, assuming the rotational angle θ_p to be very small [26].

$$\boldsymbol{F}_H = \begin{Bmatrix} F_{H,x} \\ F_{H,y} \end{Bmatrix} \cong \frac{N}{R}\begin{Bmatrix} u_{H,x} \\ u_{H,y} \end{Bmatrix} + \mu N \frac{1}{\|\dot{u}_H\|}\begin{Bmatrix} \dot{u}_{H,x} \\ \dot{u}_{H,y} \end{Bmatrix} \tag{1}$$

where N is the axial load on the CSS bearing corresponding to the axial pressure $p = N/S$. It is worth noting that the overall force-displacement law for a double CSS bearing can be obtained by considering two single CSS bearings acting in series. From equilibrium, the horizontal forces on each surface are equal but the displacements and velocities are not. Thus, the same response of a single CSS bearing is generally not obtained even if the same radius of curvature and friction coefficient are assumed for both sliding surfaces (i.e. symmetrical double CSS bearing).

2.1. CALCFC model: constant axial load and constant friction coefficient

For constant values of the axial load (i.e. $N = W$, W being the weight of the superstructure) and friction coefficient, the force-displacement behaviour of the CSS bearing in the horizontal direction ($\boldsymbol{F}_H$-$\boldsymbol{u}_H$) can be idealized by means of a two-component model (Fig. 2a), consisting of an elastic component with restoring stiffness $K_r = W/R$ and an elastic-plastic component with elastic stiffness K_i-K_r and yield force $\nu\mu W$, being $\nu = (\mathrm{Ki}-\mathrm{Kr})/\mathrm{Ki}$, assuming a bilinear force-displacement law (Fig. 2b). It should be noted that the initial stiffness K_i takes into account the slight deformation (i.e. $\boldsymbol{u}_{Hi} \cong 0.5$ mm) at the sliding surface during the stick phase [27]. Moreover, a circular interaction domain can be used to represent the biaxial interaction (Fig. 2c), where the direction of the hysteretic force is controlled by the incremental plastic displacements [28].

2.2. CALVFC1 model: constant axial load and variable friction coefficient with velocity

The instantaneous sliding velocity affects the friction force of a CSS bearing (Fig. 3a,b), with a monotonic increase with the sliding velocity up to a constant value [19]. An exponential law can describe the velocity dependence of the friction coefficient (Fig. 3c):

$$\mu(\dot{u}_H) = \mu_{fast} - (\mu_{fast} - \mu_{slow})e^{-\alpha \dot{u}_H} \tag{2}$$

where μ_{slow} and μ_{fast} are the friction coefficients at low and fast sliding velocities, respectively, and α is a rate parameter which depends on the axial load and condition of the interface.

In particular, experimental results indicate that the dynamic-slow friction coefficient can be assumed 2.5 times lower than μ_{fast} [29], while parameter α can be considered equal to approximately 0.1 s/mm in accordance with the law [8]:

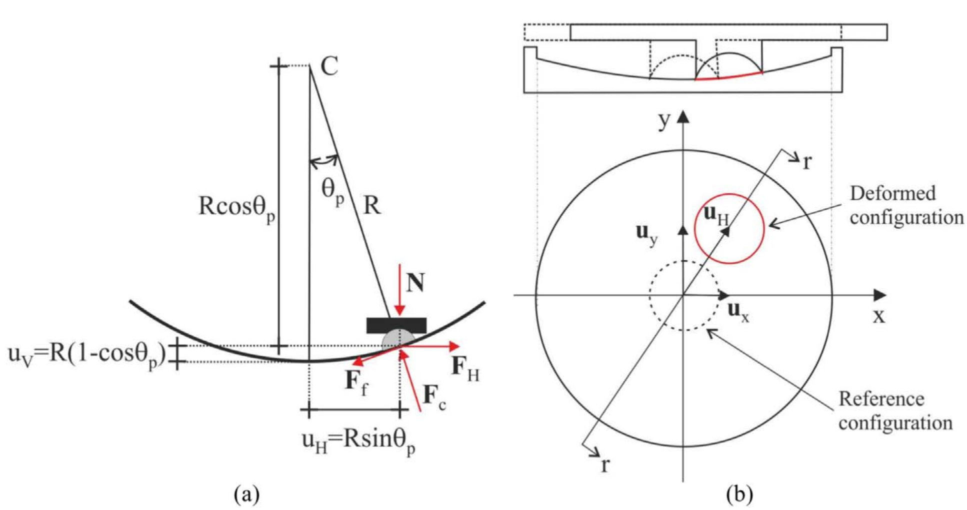

Fig. 1. Equilibrium of a CSS bearing for bidirectional motion.