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Analytical and finite element investigation on the thermo-mechanical coupled response of friction isolators under bidirectional excitation

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ABSTRACT

The hysteretic behavior of friction concave isolators is affected by the variability of the friction coefficient experienced during a seismic event. This variability is a combined function of axial load, sliding velocity and temperature rise at the sliding surface, the latter being responsible for significant friction degradation. Experimental testing and corresponding numerical models are usually focused on the monodirectional performance of the friction isolators, although multi-directional paths occur in a real earthquake scenario. In this paper, the thermo-mechanical coupled (TMC) response of friction concave isolators when subjected to bidirectional excitation is investigated in both an analytical and a numerical framework. First, a simplified phenomenological model is presented that accounts for the friction degradation due to the distance traveled via a macroscale cycling variable, based on the assumption of a uniform heat flux at the sliding interface. Then, a more sophisticated numerical investigation is performed via a TMC finite element (FE) model. A customized subroutine has been developed and implemented into the FE code to account for the local variation of the friction coefficient due to the local temperature rise and sliding velocity. The mutual interaction between mechanical and thermal response is incorporated in the proposed computational approach: the friction-induced temperature rise on the contact points and the consequent friction degradation caused by heating phenomena are analyzed as two interconnected phenomena in a recursive fashion. The friction coefficient law at the sliding interface is adjusted step-by-step and is different from node to node on the basis of the temperature distribution. Validated against experimental data, the two proposed models are used within a parametric study to scrutinize some interesting features observed in the thermo-mechanical response of friction isolators.

1. Introduction

The friction concave isolator, also known under the nomenclature curved surface slider (CSS) or the trademark name friction pendulum™ bearing [1,2], is a widely used device for seismic protection of bridges [3–5], buildings [6–10] and industrial facilities. The increasing popularity of friction sliding bearings can be ascribed to some attractive features as compared to other isolators (e.g. elastomeric bearings) having similar characteristics. The self-centering action is induced by the pendulum operating principle, while the energy dissipation is controlled by the tribological properties of the sliding materials.

Significant advances in the manufacturing process of sliding materials have been recently made by material science and technology, so that high-performance materials having enhanced durability, mechanical and physical characteristics under the range of operating conditions typically occurring during a seismic event can be obtained. Generally, high-bearing-capacity polymer composites like polytetrafluoroethylene (PTFE, Teflon®), PTFE-based compounds with fillers or other enhanced variants of thermoplastic, self-lubricating polymers such as ultra-high-molecular-weight polyethylene (UHMWPE) are employed. The aim of experimental testing is to investigate the response of friction concave isolators under such seismic service conditions. The frictional behavior of sliding materials was investigated in a number of research works, see e.g. [11–16], to quote just a few. Investigating new sliding materials for sliding isolation bearings is also of significance for companies involved in the design and manufacturing of seismic isolation hardware, especially R&D departments.

Despite the progress made in manufacturing technology, *friction degradation* and wear in thermoplastic materials adopted at the sliding interface cannot be avoided altogether. Indeed, the friction coefficient measured in experiments is not constant (stable) as postulated by the simplified Coulomb model, but depends upon the operating conditions, especially contact pressure, sliding velocity and repetition of cycles that induces temperature rise. In particular, frictional heating alters the

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physical properties of the contact materials, and causes a degradation of the mechanical performance of the isolation device. Therefore, measurements of local temperature at the sliding interface are highly desirable for the selection, assessment and development of new friction materials for isolators. Nevertheless, it is extremely difficult to measure the temperature at the sliding surface while the slider is in motion: in the literature, temperature measurements were either restricted to small-scale tests [13] or at most limited to an indirect assessment using thermocouples embedded into the sliding surface [17,18] at a certain depth below the sliding interface. As a result, analytical and, above all, numerical (finite element) models are a useful complement to experiments in order to gain an insight into the frictional heating, to quantify the friction degradation for test conditions other than those prescribed by testing protocols, or simply to design experiments on the basis of principles of scaling when testing of full scale specimens is not possible (like those described in [17]).

On the one hand, simple *analytical models* were developed based on equilibrium conditions and some kinematical and phenomenological assumptions [19,20,14]. Typically, the effect of the sliding velocity on the friction coefficient can be easily incorporated, while the temperature influence on the friction degradation is usually considered in a simplified manner by means of an equivalent macroscale (cycling) variable, such as the amount of work done [21,22], an average heat flux [17], a parameter quantifying the energy dissipated over repetition of cycles [23,24] or a representative temperature at a [25,26]. The local temperature variable has been introduced by Monti and Petrone [27] in a 3D analytical model by means of an additional differential equation based on the energy rate balance. All these simple analytical models lend themselves to straightforward implementation for response history analysis, but cannot describe the local temperature distribution or the local variation of the friction coefficient as long as only average variables are adopted. Moreover, most of these studies calculated the thermal solution independently from the mechanical one, thus they did not address the coupled thermo-mechanical response of the sliding isolator in an interconnected way.

On the other hand, *numerical models* based on finite elements and computational algorithms were adopted to capture the temperature distribution or other response quantities in a local manner, thus outperforming the above average descriptions. Drozdov et al. [28–30] investigated the tribological characteristics of self-lubricating materials for use in sliding friction bearings and studied the temperature field across the sliding surfaces by means of the finite element (FE) method. The aim of their study is to guide the choice of self-lubricating materials on the basis of thermal stability and endurance. However, they did not investigate the effect of the temperature on the degradation of the friction coefficient. Quaglini et al. [18] proposed a three-dimensional finite element (FE) model and studied the influence of the temperature rise on the friction degradation by implementing a temperature-dependent friction law into the FE code. Although the latter model was of general validity, the investigation was limited to monodirectional paths, and the comparison between monodirectional and bidirectional motion in terms of hysteretic loops, contact pressures and temperature fields was not the main aspect examined in the quoted study [18].

1.1. Goal of the paper and research significance

In order to bridge the gap between the aforementioned classes of analytical (simplicity) and numerical (complexity) models, the goal of this paper is to investigate the thermo-mechanical coupled (TMC) response of friction concave isolators via both an analytical and a numerical approach for comparative purposes. A friction model that neglects the temperature rise and its effect on the degradation of the mechanical performance would lead to underestimate the displacements expected during seismic events and to overestimate the dissipative capacity of the isolator accordingly. Experiments [31–33] also show that similar outcomes would be achieved by ignoring the bidirectional interaction and considering unidirectional excitations as if the components of a multidirectional path (a real earthquake scenario) were uncoupled. The main motivation of this study is to scrutinize some differences observed in the device response when subject to monodirectional and bidirectional motion, not only in terms of force-displacement hysteretic loops and energy dissipated, but also with regard to contact force distribution between the sliding surfaces, kinematics of the device, directionality of the horizontal resisting force, as well as temperature distribution at the sliding interface. A *macroscale phenomenological model* is first presented to describe the variation of the friction coefficient as a combined function of axial load, sliding velocity and temperature rise. According to the previous remarks, the temperature rise in this analytical model is not computed in a local sense, but in an average sense: it has been indirectly considered through the distance traveled via a macroscale cycling variable, based on the simplifying assumption of a uniformly distributed heat flux at the sliding interface. To convert the macroscale, cycling variable into a microscale, local temperature variable, a more sophisticated *TMC three-dimensional FE model* is developed. In particular, the generation of frictional heat is simulated via a moving heat source with local intensity dependent upon the instantaneous friction coefficient, the relative velocity and the contact pressure at the sliding surface. The friction coefficient law is iteratively adjusted (step-by-step) at each nodal point of the FE model (node-by-node) on the basis of the local temperature rise, and the updated friction value is used to compute the heat flux at the next time step. The mutual interaction between mechanical and thermal response is incorporated in the proposed computational approach: the friction-induced temperature rise on the contact points and the consequent friction degradation caused by heating phenomena are analyzed as two interconnected phenomena in a recursive fashion [34], in the spirit of a truly coupled thermo-mechanical analysis. A *customized Fortran subroutine* governing the friction coefficient as a function of axial load, sliding velocity and local temperature has been specifically developed and implemented into the FE code. This function has a similar shape to the friction law of the above phenomenological model, which is useful to check the consistency of the results obtained by the two models for calibration and comparison purposes. Attention is focused on the distinctive behavior observed in friction sliding bearings when subjected to multi-directional excitations like in a real earthquake scenario. First, we validate the two proposed models against experimental data concerning cloverleaf bi-directional tests. Also monodirectional tests with the single cloverleaf components are analyzed so as to highlight the salient differences in comparison with the bi-directional counterpart. The analysis of the kinematics of the device and the assessment of the contact force distribution between the sliding surfaces highlight some interesting features about the pendulum mechanism and the directionality of the horizontal resisting force. Then, a wide-ranging parametric study is carried out in order to investigate the coupled thermo-mechanical response of the friction concave isolator under a few bi-directional orbits and to further validate the proposed relationship between analytical and numerical models.

2. Fundamentals of the mechanical behavior

Some basic, general concepts underlying the mechanical behavior of friction sliding bearings that will be useful in the sequel of the paper are here summarised. In its single concave configuration, cf. Fig. 1a), the friction isolator is composed of: *i*) a primary, lower sliding surface made of polished stainless steel and having a concave profile with curvature radius R, which determines the natural period of vibration and allows the horizontal movement according to the pendulum operating principle; *ii*) an upper steel plate featuring a secondary concave sliding surface via an internal semi-spherical articulation of radius r, the latter permitting the rotation and assuring the kinematic compatibility of the overall motion. In between these two opposed surfaces a lentil-shaped articulated steel slider is placed, whose upper and lower external