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FINITE ELEMENT MODELING OF SINGLE AND MULTI-SPHERICAL FRICTION PENDULUM BEARINGS

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Abstract. *Base isolation is a modern strategy to decrease the effects of earthquakes on buildings of high significance. The general principle is that the structure is decoupled from the horizontal components of the earthquake ground motion by interposing a layer with low lateral stiffness between the structure and the foundation. One of the major devices to apply seismic isolation is Friction Pendulum Systems, which use the characteristics of a pendulum to lengthen the natural period of the isolated structure. These systems consist of an upper and a lower spherical plate with sliding surface applied with special coating, and an articulated slider. The aim of this paper is to simulate Friction Pendulum Isolation Systems, using the finite element method. All models are constructed using full three dimensional continuum modeling in ABAQUS software. Particularly, this study includes single, and multi-spherical Friction Pendulum Bearings simulation. Dynamic time history analyses are performed and results in terms of hysteretic loops are presented. The analyses results of the proposed models are verified with the analytical solution of the friction pendulums response and with those obtained by analyses in other commercial software which contains Friction Pendulum Bearing model.*

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1 INTRODUCTION

Base isolation consist an intervention technique which aims to relieve the structure from the ground motion excitations. Introducing isolation devices in a certain level, a base with low lateral stiffness is generated. Due to this fact the superstructure is decoupled from the ground, and as a result the seismic forces are significantly reduced [1]. Two main categories of base isolation devices are in use, the rubber bearings [2] and the friction ones [3]. The main devices based on the friction mechanism are the friction pendulum (FP) bearings. Their application in buildings [4] are growing the current year.

The single friction pendulum (SFP) bearings have been studied since 1990 [3, 5, 6]. A FP is composed by an articulated slider that moves on a concave spherical surface. The surfaces in which sliding occurs, are coated to a low friction material. Based on the pendulum function, the superstructures period depends on the curvature R of the FP bearing.

Due to the concave surface, re-centering forces are introduced, which are proportional of the superstructure weight. During the last decade sliding bearings with adaptive seismic behavior are presented [7-9]. The adaptive response is achieved by using multi-spherical sliding devices. Based on this, double friction pendulum (DFP) triple friction pendulum (TFP) and even quintuple friction pendulum (QFP) bearings are developed [10-13]. The DFP are consist of two concave surfaces, the TFP of four surfaces and the QFP of six sliding surfaces.

Modeling principles of these systems are discussed by, Morgan and Mahin [8], Tsai et al. [9], Fenz and Constantinou [11], Sarlis and Constantinou [12], Becker and Mahin [14] among others. A simulation model of a sliding bearing have to obey some basic principles. First, it is required to have the capability of simulating the overall force-deformation behavior. Moreover, it has to track the sliding of the individual interfaces and simulates when the restrainer is hit. A secondary but very interesting attribute of a simulation model is to take into account the uplift of the individual parts.

2 EXAMINING FRICTION PENDULUM BEARINGS

In this study a finite element modeling approach for the simulation of friction pendulum bearings is presented. Single friction pendulum (SFP), double friction pendulum (DFP) and triple friction pendulum (TFP) bearings are simulated and their models are validated. In Figure 1 the main characteristics of single and multi-spherical isolators are depicted. These characteristics are, each surfaces curvature (R) and coefficient of friction (μ), the displacement capacity of each surface that sliding occurs (d) and finally the radial distance between the spherical surface and the pivot point of the articulated slider (h) by which the effective curvature is calculated ($R_{eff,i} = R_i – h_i$).

Regarding the DFP it was selected for the concave surfaces to have the same curvatures $R_1 = R_2$ and the same coefficients of friction $\mu_1 = \mu_2$. By this, it model could be easily verified with the response of a SFP bearing with $R_{eff} = R_{eff,1} + R_{eff,2}$. The examined TFP bearing was considered with the same curvature and coefficient of friction for the two inner and the two outer surfaces ($R_1 = R_4$, $\mu_1 = \mu_4$ and $R_2 = R_3$, $\mu_2 = \mu_3$). In Table 1 the main properties of the FP bearing considered in this study are listed.

Model	**R_1 (m)**	**R_2 (m)**	**$R_{eff,1}$ (m)**	**$R_{eff,2}$ (m)**	**μ_1**	**μ_2**	**T_1 (s)**	**T_2 (s)**
SFP	1080	-	1	-	0.1	-	2	-
DFP	650	650	0.5	0.5	0.1	0.1	2	-
TFP	2050	530	2	0.5	0.1	0.03	4.65	2

Table 1. Simulated friction pendulums characteristics.

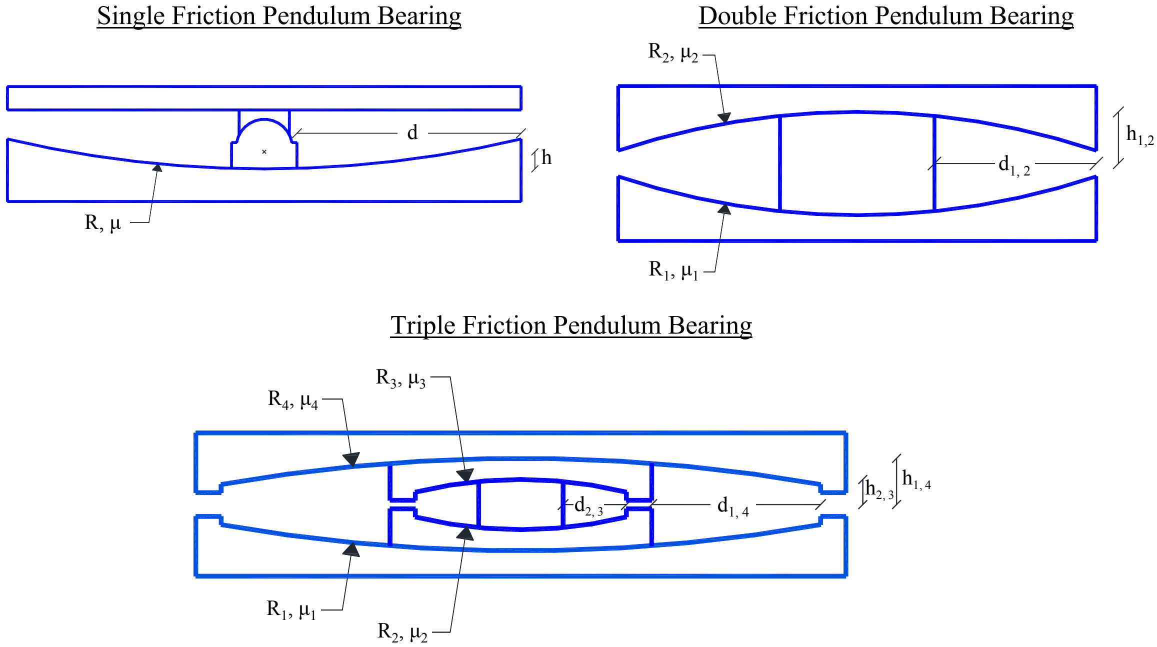

Figure 1. Cross sections of friction pendulum bearing.

A first task is to define the force-displacement relations in order to construct the hysteretic loops of the bearings (Figure 2). The force-displacement relationship that governs the SFP and the DFP as it configured above is given by the following equation:

$$F = \frac{W}{2R_{eff}} u + \mu W \tag{1}$$

where W is the axial force of the bearing, $R_{eff} = R_{eff,\,1} + R_{eff,\,2}$ for the DFP and u is the displacement that the device develops.

The TFP with the same properties in the outer and inner surfaces operates with three different schemes, which activation depends on the level of the seismic excitation following the attributes: (a) high damping and stiffness at low level forces; (b) low stiffness at moderate level earthquakes; and (c) high damping and high stiffness at severe level earthquakes. That adaptive response is achieved through a progressive activation of different sliding surfaces.

When sliding occurs to the inner surfaces (Region I) the force displacement is calculated by the following equation:

$$F_1 = \frac{W}{2R_{eff2}} u + \mu_2 W \tag{2}$$

When the outer surfaces are activated (Region II) the lateral forces are calculated by Eq (3)

$$F_2 = \frac{W}{2R_{eff1}} u + \left[\mu_1 - (\mu_1 - \mu_2) \frac{R_{eff2}}{R_{eff1}} \right] W \tag{3}$$

While when the displacement capacity of the outer surfaces are reached, the inner ones are activated again (Region III) and the forces are given as follows.

$$F_3 = \frac{W}{2R_{eff2}} (u - u^{**}) + \frac{W}{R_{eff1}} d_1^{*} + \mu_1 W \tag{4}$$

where $d_1^{*} = d_1 (R_{eff\,1} / R_{eff})$ and $u^{**} = 2(\mu_1 - \mu_2) R_{eff\,1} + 2d_1^{*}$

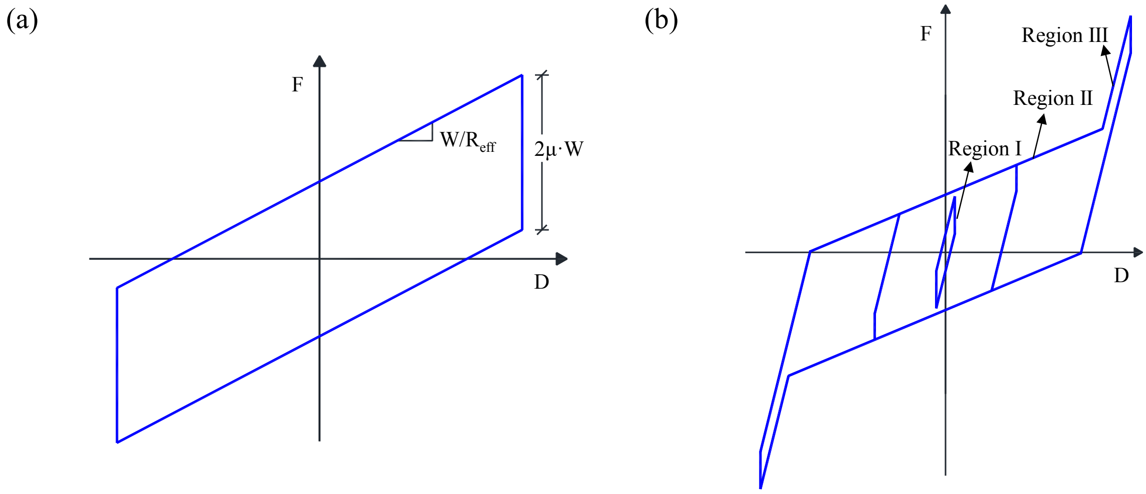

Figure 2. Force-displacement relations for (a) a SFP and a DFP and (b) for a TFP.

3 FINITE ELEMENT MODELING

The FP bearings are simulated with full three dimensional continuum modelling by using solid element in ABAQUS software [15]. The FP components material are considered as homogenous isotropic, with Young's Modulus equal to E = 210 GPa a Poisson ratio v = 0.3. All the parts are meshed using 8 node linear brick elements C3D8R. Hourglass control was adopted to minimize the effects of spurious/hourglass modes effects that may be initialized by the reduced integration elements that are used. Mesh size was moderate considering acceptable and reliable results as well as the computational time. The detailed model of the FP bearings geometry (Figure 3) allows a complete description of it kinematic behavior, accounting the restoring forces, variation of contact pressure as a consequence of overturning moments, and uplift [16].

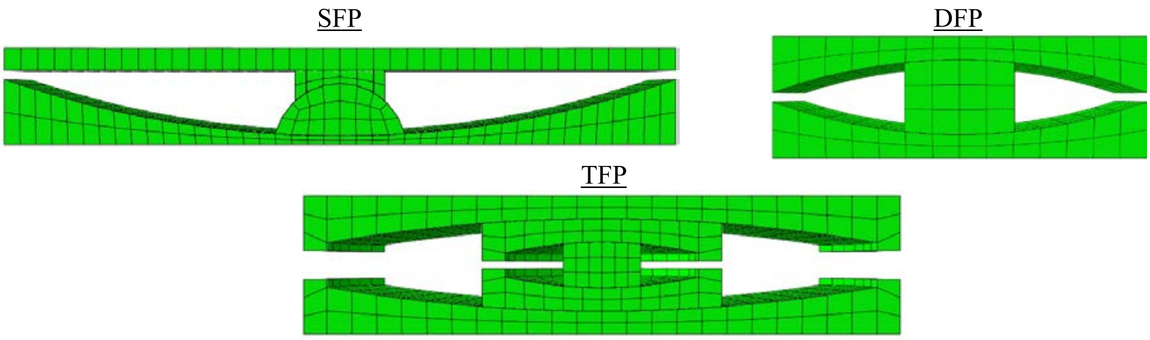

Figure 3. Finite element models of the examined FP bearings

Regarding the friction which is the most important characteristic for the operation of the FP bearing, rigid contact is used to model the interfaces between the isolators' parts. In literature [17] it has been thoroughly investigated the influence of the friction models adopted for the analyses. Comparing Coulomb friction model with other more sophisticated which took into account the sliding velocity [6], the pressure or the temperature, have been concluded that the Coulomb friction is adequate to simulate the friction of the sliding surfaces of a FP bearing. Thus, a Coulomb model is adopted to describe the tangential behavior between the sliding surfaces. For the normal direction of the contact element, the stiffness is assumed as infinite.

A simplified analysis model are selected to verify the finite element models of the isolation bearing (Figure 4). That model consist of two identical bearings connected with a rigid and massless beam. The gravity loads W are considered at the top of the isolators, while the ground motion excitation are applied at the base in terms of seismic acceleration. Four ground motion records are used for the validation of the models (Table 2).

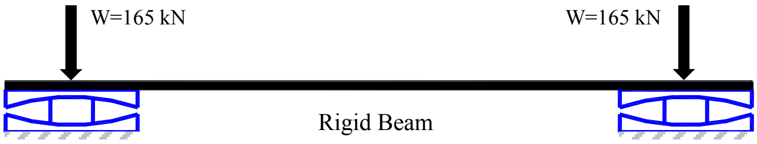

Figure 4. Analysis model.

Earthquake	Station	Date	M_S	R (km)
Kobe	Nishi -Akashi	16/1/1995	6.9	7.08
Chuetsuoki	Nakanoshima Nagaoka	16/7/2007	6.8	19.89
El Mayor Cucapah	Chihuahua	4/4/2010	7.2	19.47
Chi-Chi	CHY101	20/9/1999	7.62	9.94

Table 2. Ground motion records list.

4 RESULTS

The validation of the models are performs by comparing two individual results. First, the Force–Displacement which consist the most representative result that indicates the appropriate operation of the bearing. In more detail, it highlights the correctly sliding movement between the FP parts. Moreover, another feature that point out the effectiveness of the FP bearings in the superstructure are the accelerations at the level of the isolated base. Results obtained by the similar analysis problem, performed in SAP2000 software, in which the bearing are simulated with link elements, are used in order to validate the results of the proposed model.

4.1 Single Friction Pendulum

In Figure 5 the hysteretic loops of the proposed model are compared with the loops of the analyses in the SAP200 software. The ground motion records induce to the bearings maximum displacements ranged from 0.044 m to 0.165 m. Thus, the performance of the isolators to different operation levels are examined. As observed in Figure 5, the proposed model is in great agreement with the results of the commercial program. FP features like the stiffness and the hysteretic loops' width are the same with the analytical ones. Regarding the developed displacements minor alteration are displayed between the models. Moreover, due the type of the proposed model any variation of contact pressure can be captured in the results.

In Figure 6 the acceleration of the isolated base is demonstrated. The amplitude results from both models are alike. Furthermore, the time histories of the accelerations are identical. The only difference is that the proposed model results are sharper than the results of the model with link elements.

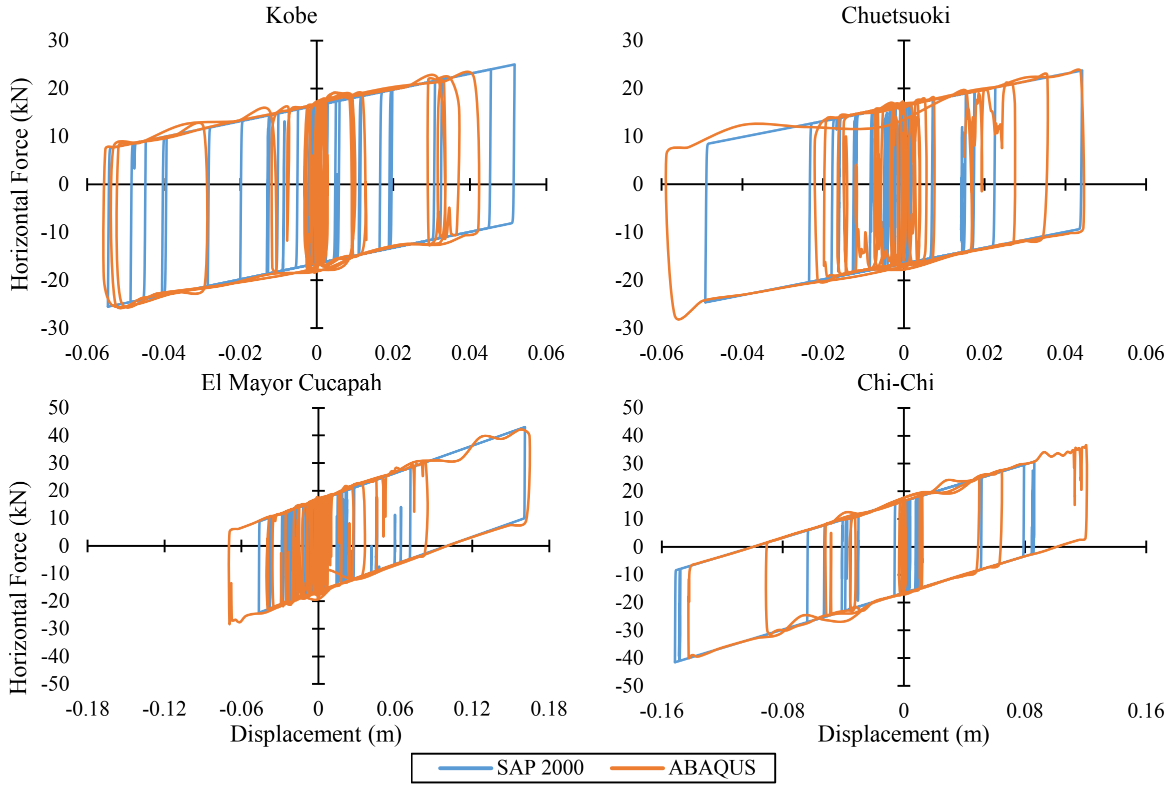

Figure 5. Comparison of SAP2000 and ABAQUS models Force-Displacement loops.

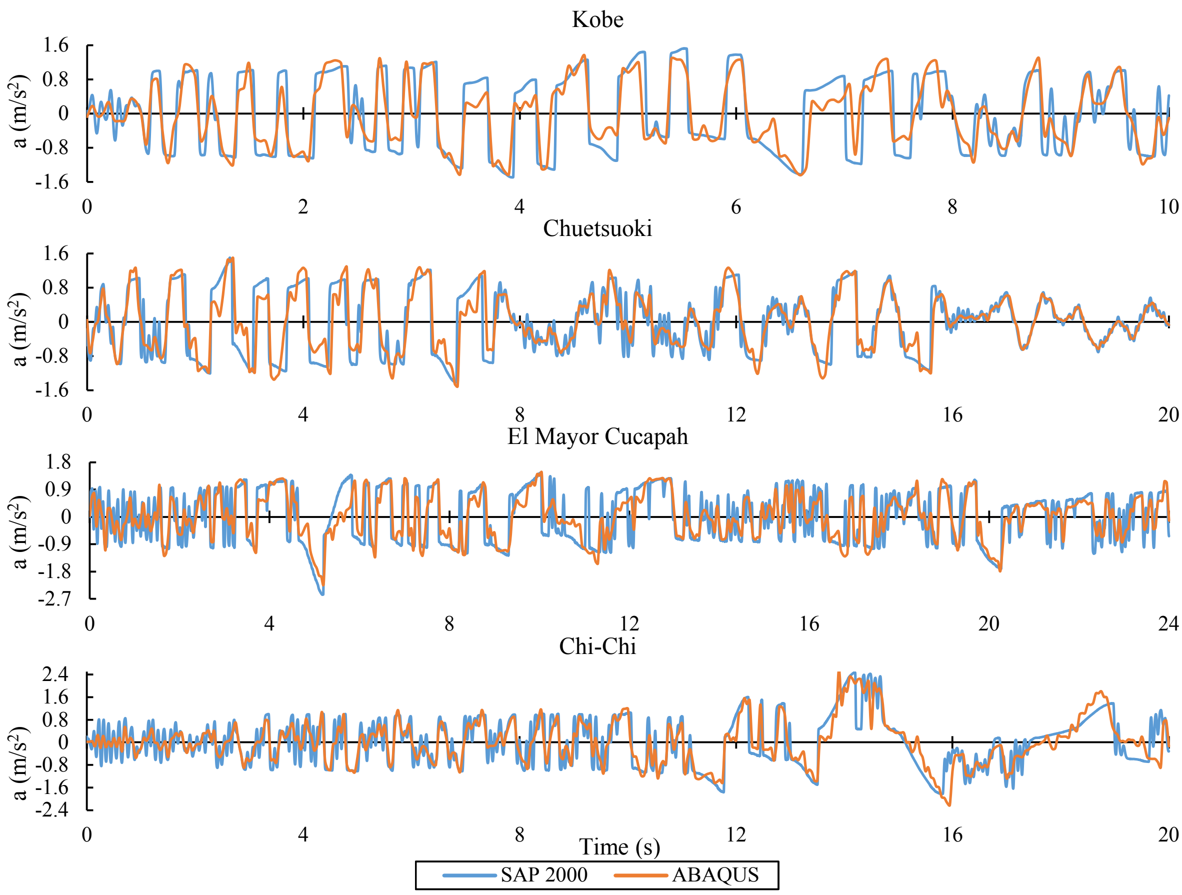

Figure 6. Comparison of SAP2000 and ABAQUS models accelerations.

4.2 Double Friction Pendulum

The DFP bearings with curvatures $R_1 = R_2$ and coefficient of friction $\mu_1 = \mu_2$, performs similar to a SFP bearing with curvature $R = R_1+R_2$ and $\mu = \mu_1 = \mu_2$. Therefore, the results of the DFP are compared with those of the equivalent SFP. In Figures 7 and 8, are presented the hysteretic loops and the accelerations of the analysis model respectively. Considering the force displacement loops the results have similar characteristics, as it should be. It can be observed that the DFP results are even closer to those obtained by SAP2000 (Figure 6). Regarding the acceleration of the isolated base, the values are equivalent between teach other. As remarked for the hysteretic loops, the acceleration of the DFP are smother and identical with those of the modeling with link elements results.

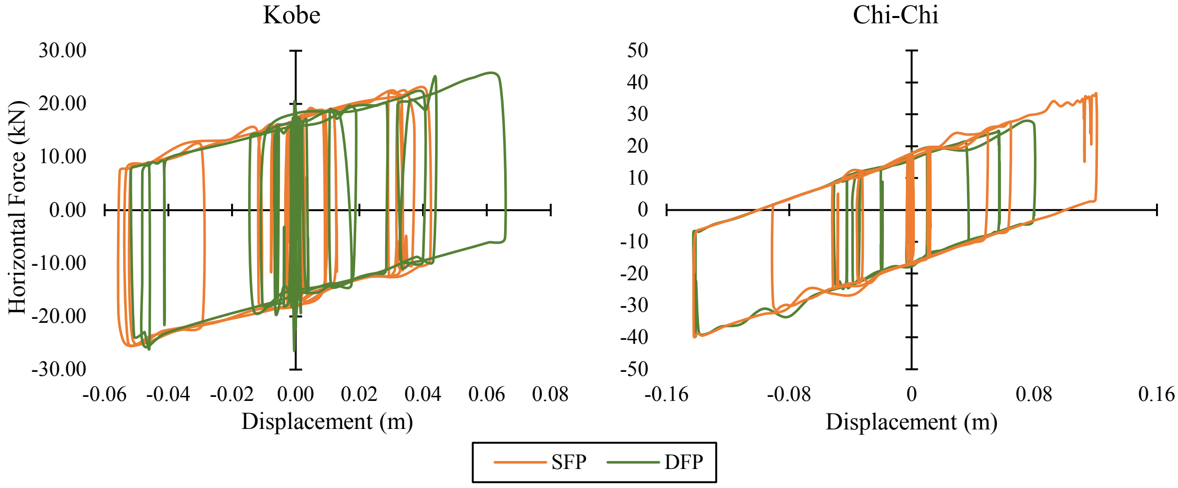

Figure 7. Comparison of SFP and DFP Force-Displacement loops.

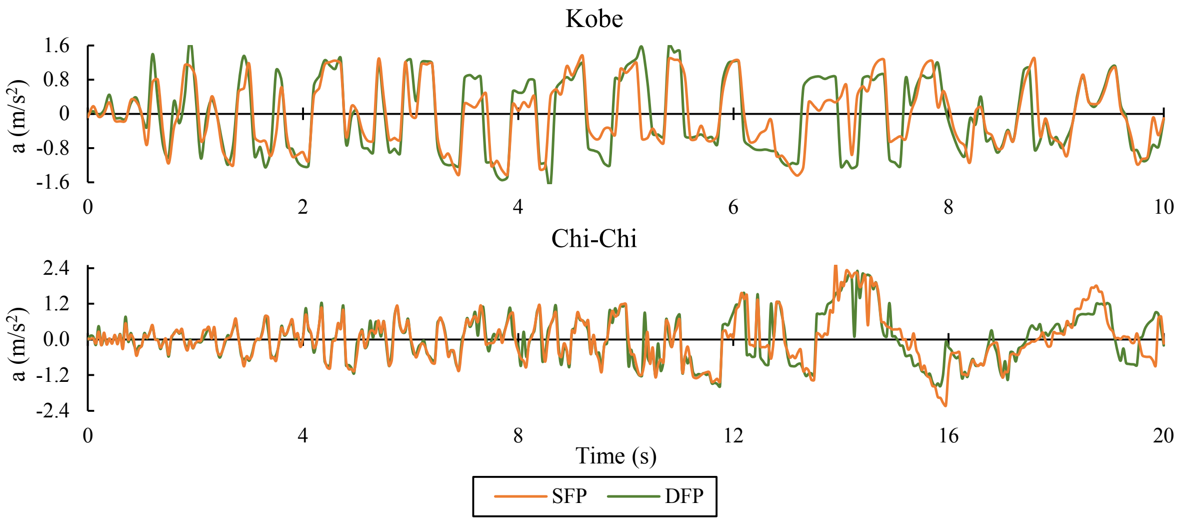

Figure 8. Comparison of SFP and DFP accelerations.

4.3 Triple Friction Pendulum

The examined TFP bearing has such curvatures that correspond to isolated period T_2 =2 s when the inner surfaces are activated and to T_1 =4.65 s, when sliding occurs on the outer surfaces. Results in terms of acceleration time histories are presented. In Figure 9 the accelerations of the isolated base supported to the DFP and the TFP are displayed. Two interesting fact are arose throughout this comparison. First the TFP devices reduce the acceleration values more than the DFP ones and especially of the Kobe excitation, which has a higher frequency content. Second, due to the actuation of the outer surfaces, it lengthens even more the acceleration signal.

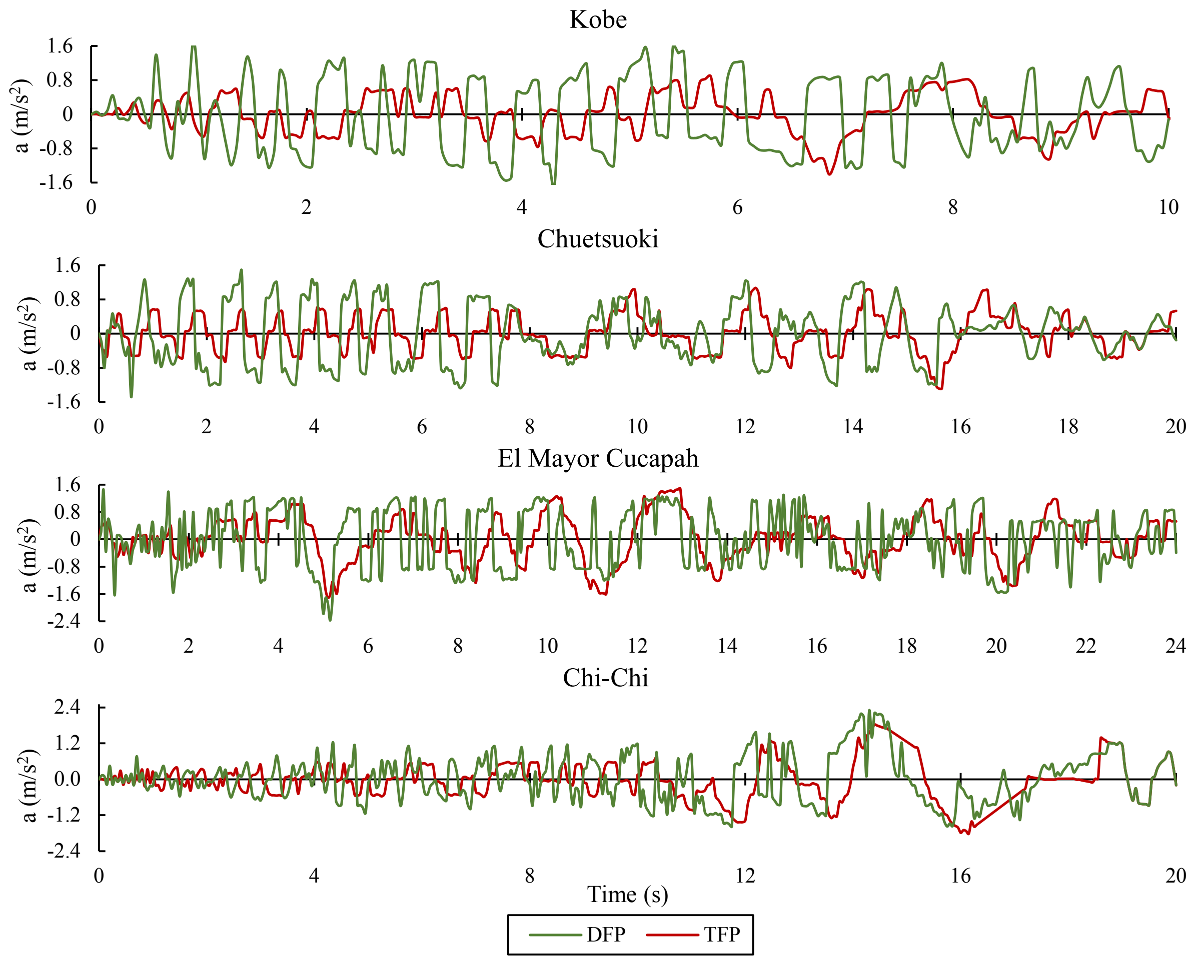

Figure 9. Comparison of DFP and TFP accelerations.

5 CONCLUSIONS

A proposed finite element simulation of single and multi-spherical friction pendulum bearings is examined in the present study. Single, double and triple friction pendulum isolation devices are simulated in ABAQUS software. A simple analysis model is adopted and time history analyses using four ground motion records are performed to verify the results of the FP finite element models. The analyses results are contrasted with those obtained by link isolator modeling in the commercial program SAP2000.

The results are satisfactory as the proposed models could estimate with great accuracy the seismic response of the FP bearings. Moreover, due to the type of the simulation it took into account the restoring forces and the variation of contact pressure due to overturning moments and uplift. Firstly, by the hysteretic loops, the characteristic values such as the stiffness and it width are correctly given. The force-displacement results are much similar for both SFP and DFP bearings. Furthermore, the acceleration transmitted through the isolation devices are acceptable as they are identical between the models. Finally, comparing the acceleration results of the TFP with those of the DFP, the superior performance of the former are highlighted.

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