SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

SEİSMİC PERFORMANCE OF A STRUCTURE WITH DOUBLE CONCAVE FRICTION PENDULUM ISOLATİON SYSTEM.

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ABSTRACT

An extensive experimental seismic testing programme, named project JETBIS (Joint Experimental Testing of Base Isolation Systems), has been developed within the RELUIS (2010-2013) project - Task 2.3.2, involving partners from different Italian universities. This paper describes the tests performed on seismic devices based on Double Concave Friction Pendulum (DCFP).

In order to assess the fidelity of the considered non-linear model under uni-directional motion, controlled-displacement and seismic-input experiments were conducted using shaking table at University of Basilicata and at University of Naples "Federico II", respectively. The DCFP isolator contains two separate concave sliding surfaces and exhibits different hysteretic properties at different stages of displacement and velocity response. The numerical model of DCFP used is general so that no condition regarding bearing properties, which effect the sequence of sliding stages, are required for the validity of the model. The experimental model for seismic tests was a 1/3 scaled steel framed structure with one storey and one bay in both directions. Four DCFP bearings with equal properties of the concave sliding surfaces were mounted under each column.

The main objective of this work is to evaluate the effectiveness of nonlinear modelling considering two different finite element programme SAP2000 and CDS-Opensees to investigate on influence of the sliding velocity and of the vertical load on the behavior of DCFP devices under different condition of the sliding surfaces (with and without lubrication). A further goal was to verify the reliability of the numerical models also when large residual displacements due to previous earthquakes are present in the isolation system. In this paper the experimental outcomes of various testing model configurations are compared with the results of non linear dynamic analysis obtained by both numerical simulations.

INTRODUCTION

The seismic design of base isolation systems is a worldwide widespread application in order to make structure more resistant to earthquake ground motions. The underlying concept of base isolation is the uncoupling of horizontal building movement from ground motions using a flexible isolation layer made with either elastomeric (rubber) bearings or sliding bearings (Cardone et al., 2005) Sliding isolators use velocity dependent friction between composite materials, usually composed of polyethylene, and stainless steel plates as its energy dissipation system. Most of the seismic isolation

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systems currently in use provide friction properties as their energy dissipation mechanism. Theoretical and experimental research studies have been focused on developing more versatile and economic isolation systems such as friction pendulum (Becker and Main 2012; Dao et al. 2013). The friction pendulum bearing (FPS), proposed by Zayas et al. (1987) is a sliding seismic isolation system which uses its surface curvature to generate the restoring force from the pendulum action of the weight of the structure on the FPS. The natural period of the isolated structure becomes independent by the mass of the superstructure, as it only depends on the radius of the sliding surface (Kim and Yun 2007).

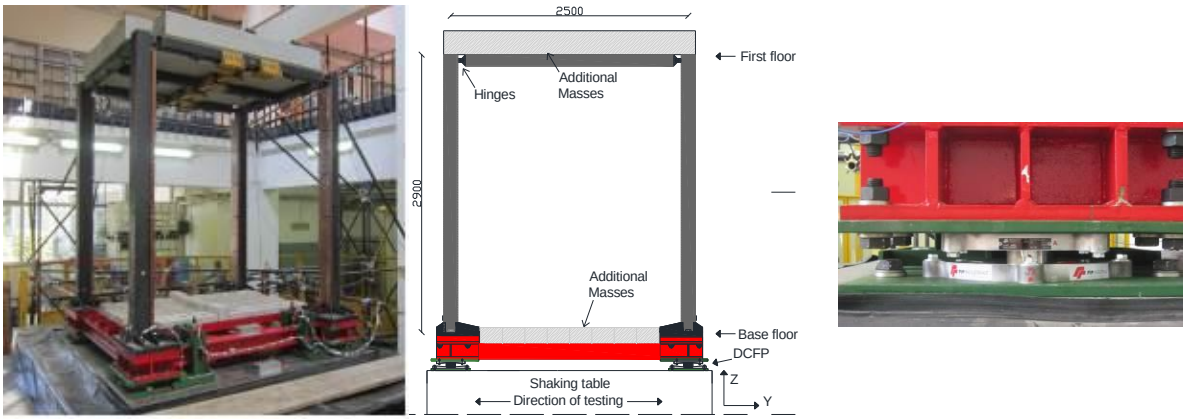
The double concave Friction Pendulum (DCFP) bearing is an adaptation of the well-known single concave Friction Pendulum Sliding (FPS) bearing. The principal benefit of the DCFP bearing is its capacity to accommodate larger displacements compared to a traditional FPS bearing of identical plan dimensions. Moreover, there is the capability to use sliding surfaces with varying radii of curvature and coefficients of friction, offering the designer greater flexibility to optimize performance (Fenz and Constantinou 2006; Malekzadeh and Taghikhany, 2010). Recently various studies (Kim and Yun, 2007) have been carried out on DCFPs revealed that tri-linear behaviour of a DCFP can be achieved by combining two FPS having different friction coefficients.

Experimental testing (controlled-displacement and seismic-input) on Double Concave Friction Pendulum bearings have been performed within the JETBIS project in order to assess their fidelity of the non-linear behaviour under uni-directional motion (Ponzo et al., 2014). The experimental model for seismic tests was a 1/3 scaled steel framed structure with one storey and one bay in both directions, in this paper only the model configuration with symmetric mass is considered. The DCFP isolators have been produced by FIP Industriale containing two separate concave sliding surfaces with same radius of curvature and a rigid slider covered by UHMW-PE composite material (FIP-Industriale, 2013). Four DCFP bearings with equal properties were mounted under each column considering two conditions of the sliding surfaces (with and without lubrication).

The paper briefly describes the test set-up and testing results of various experimental model configurations. Nonlinear time history analysis considering two finite element programmes, SAP2000 and CDS-OpenSees, have been performed to reproduce and understand the experimental response. Different modelling of DCFP have been considered; in case of SAP2000 two different models dependent of sliding velocity, while for CDS-OpenSees two different models dependent of axial load. This paper compares the experimental and numerical behaviour also when initial residual displacement were present in the seismic tests.

EXPERIMENTAL TESTS

The purpose of this study is to investigate the behaviour of DCFP and their effects in different conditions of experimental base-isolation testing. The structural 3-D model for experimental seismic tests was a 1/3-scaled steel frame, 1-storey with a rectangular plan of a 2.5m span along the test direction by 2.0m in the orthogonal one, shown in Fig.1a.



a) b) c)

Figure 1: a) overview of centred mass configuration; b) lateral view of experimental test (testing direction); c) base isolation system based on DCFP bearings

The inter-storey height is 2.9m and a 250mm thick steel-concrete slab is connected to the primary beams of the first floor. The general layout of the scaled model is shown in Fig.1a. This paper considers the seismic tests on the experimental model with symmetric masses, as reported in Table.1. Bolts were used to ensure a rigid connection between the isolators and the basement of the test model, as shown in Fig.1c. The model response was recorded by a total of 16 three-directional servo-accelerometers, and 14 laser displacement transducers. More details about experimental model can be found in Ponzo et al. (2014).

Table 1. Masses of experimental model configurations.

Storey	Mass [t]
Base	3.20
1st floor	5.00
Total	8.20

The main design characteristics of single DCFP are: the maximum design vertical load N_{Ed} = 32 kN; the equivalent radius of curvature R = 1805 mm, approximately twice geometric radius of curvature of each sliding surface; an overall displacement capacity d_{max} ± 180 mm. The rigid slider is covered by an Ultra-High Molecular Weight Poly-Ethylene (UHMW-PE) high bearing capacity composite material produced by FIP (FIP-INDUSTRIALE Spa, 2013), model FIP-D 20/360 (1805) shown in Fig.2. In this application, the DCFP consists of two identical concave sliding surfaces having external diameter 300 mm, same radius of curvature $R_1 = R_2$ = 925 mm, same coefficients of friction of surfaces $\mu_1 = \mu_2$ and a rigid slider with a diameter 75 mm and height 45 mm.

Figure 2: Overview of the DCFP bearings

NUMERICAL MODELLING

The isolation systems is realized by four DCFP, one under each column, with two spherical stainless steel surfaces, both accommodating for horizontal displacements and rotations, as shown in Fig.3a. The vertical load acting on the isolator during seismic tests is N_{Sd} = 20.5 kN. The theoretical model to resemble the functioning of the DCFP was studied by Fenz and Constantinou (2006) and consists to a bi-linear force-displacement curve as shown in Fig.3b.

The non linear model with initial stiffness k_i (before sliding) has friction force F_0 (developed by the isolator at zero displacement), restoring stiffness k_r and horizontal force F (at the considered displacement d) defined by Eq.1.

$$F_0 = N_{Sd} \cdot \mu \qquad k_r = \frac{N_{Sd}}{R} \qquad F = F_0 + k_r \cdot d \tag{1}$$

When the standard used for design of structures allows to model the non linear behaviour as a linear equivalent behaviour, the effective stiffness k_e, the period T_e associated to k_e, and the effective damping ξ_e are calculated with the Eq.2.

$$k_e = N_{Sd} \cdot \left(\frac{1}{R} + \frac{\mu}{d}\right) \qquad T_e = 2\pi \sqrt{\frac{1}{g \cdot \left(\frac{1}{R} + \frac{\mu}{d}\right)}} \qquad \xi_e = \frac{2}{\pi} \cdot \frac{1}{\frac{d}{\mu \cdot R} + 1} \tag{2}$$

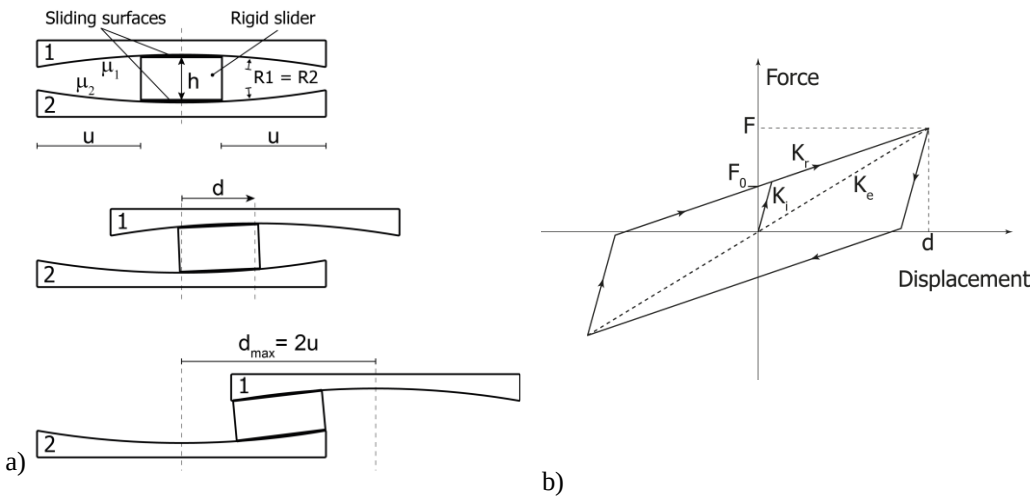


Figure 3: a) functioning scheme of the DCFP device; b) theoretical hysteresis cycle of DCFP bearing having equal radii of curvature and equal friction coefficients.

The steel frame was modelled using frame-type 3D finite elements in SAP2000 (SAP2000, 2013), Fig.4a, and CDS-OpenSees (Cds-Win, 2014), Fig.4b. The connection between the columns and the stiff beams at the base of the model was simulated through the use of fixed restraints with the floor slabs being simulated by imposing a rigid diaphragm assumption.

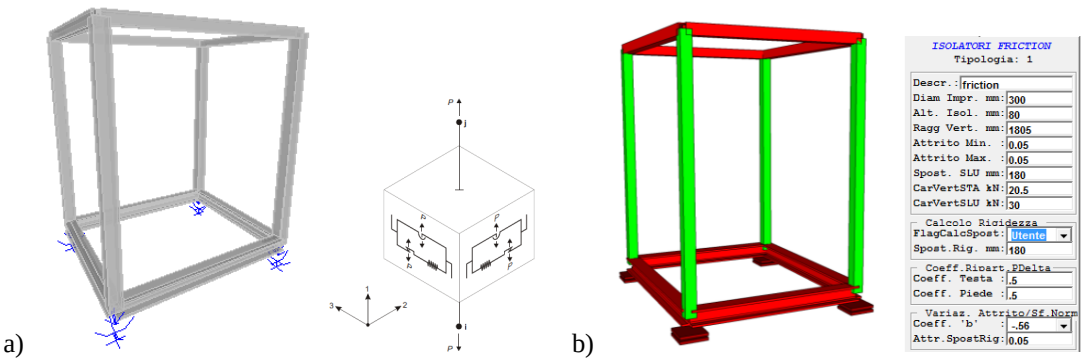


Figure 4: Global and Local modelling of the test model and DCFP: a) SAP2000, b) CDS-OpenSees.

The nonlinear behaviour of the single DCFP isolator has been modelled in SAP2000 (2013) by using one joint link element type biaxial Friction-Pendulum Isolator, see Fig.4a. The friction and pendulum forces are directly proportional to the compressive axial force in the element which cannot carry axial tension. The velocity dependence of the coefficient of friction is described by Eq.3 (Constantinou et al., 1990), where: v is the sliding velocity; μ_{fast} and μ_{slow} are the sliding coefficients of friction at maximum and minimum velocity respectively; α is a rate parameter that controls the transition from μ_{slow} to μ_{fast}.

The nonlinear behaviour of the single DCFP isolator has been modelled in CDS-OpenSees (2014) by using one Friction-Pendulum Isolator, see Fig.4b. The axial load dependence of the coefficient of friction is described by Eq.4 (FIP-Industriale, 2013), where: N_{Sd} and N_{Ed} are the vertical load acting on the isolator and the maximum design vertical load respectively; β is coefficient that controls the lubricate condition of the surfaces.

$$\mu = \mu_{fast} - (\mu_{fast} - \mu_{slow}) \cdot e^{-\alpha \cdot |v|} \tag{3}$$

$$\mu = \mu_{slow} \cdot (N_{Sd} / N_{Ed})^{\beta} \tag{4}$$

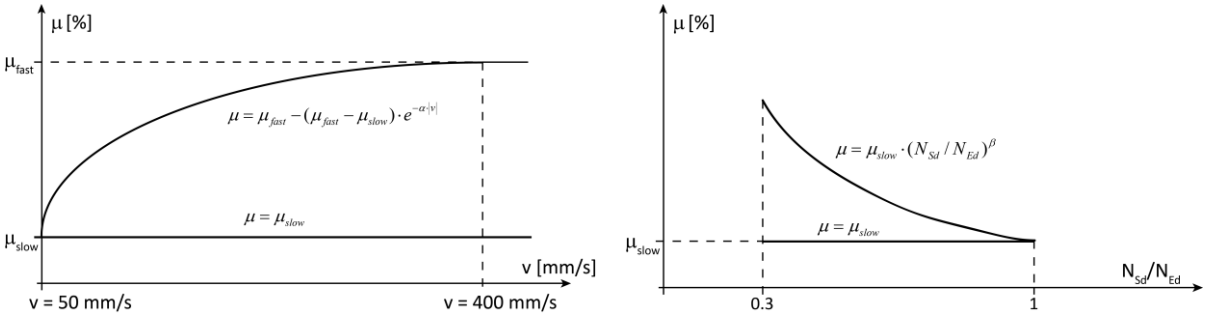


Figure 5: friction coefficient; a) sliding velocity dependence; b) dependence of axial load

EXPERIMENTAL AND NUMERICAL RESULTS

Characterization tests

The bearings were tested under a maximum design vertical load N_{Ed} = 32 kN. A series of sinusoidal lateral displacement were imposed in accordance with testing of Curved Surface Sliders prescribed by Eurocode (UNI-EN 15129, 2009). Fig.6 shows experimental force-displacement relationships of the DCFP carried out on two conditions of surfaces: i) Lubricated (SL) and ii) Not-lubricated (SNL). The sliding material is essential to give stability of the hysteretic force vs. displacement curves with displacement and velocity. A silicone based (lithium soap) lubricant was applied to the top and bottom face ($\mu_1 = \mu_2$) of the rigid slider. Major details of DCFP characterization testing can be found in Ponzo et al. (2014).

The numerical simulations with SAP2000 have been calibrated against the results of displacement- controlled tests by considering two different non-linear model of DCFP:

i) constant friction model whit a rigid-bilinear hysteretic behaviour and constant friction, as derived from benchmark test ($k_i = k_{i,slow}$; $\mu = \mu_{slow}$);
ii) variable friction model with bilinear hysteretic behaviour and velocity dependent friction, as derived from dynamic tests ($k_i = k_{i,fast}$; μ defined by Eq.3)

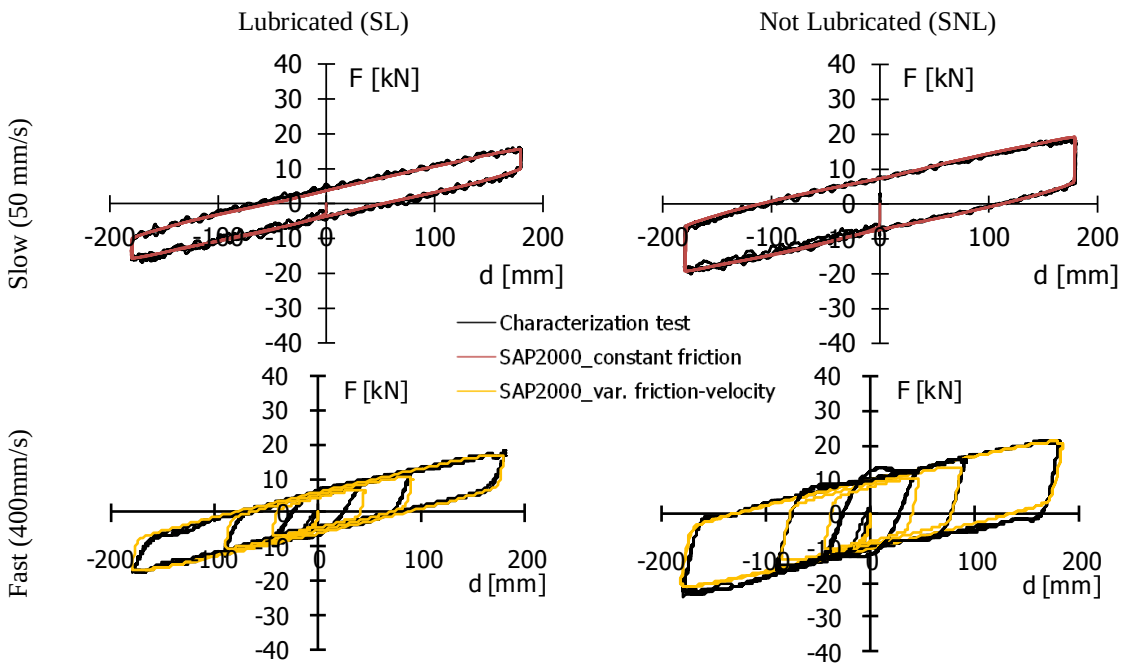


Figure 6: Experimental and numerical (SAP2000) Force–displacement at peak velocities of 50 and 400 mm/s. Both tests were conducted on Lubricated (SL) and Non-lubricated (SNL) surfaces.

Fig.6 reports the numerical results considering both constant and variable friction depending on sliding velocity, as modelled by SAP 2000. A good agreement with experimental outcomes is

observed when initial stiffness k_i, friction μ, determined by benchmark (slow) and dynamic (fast) tests, and α assuming the values reported in Table.2.

The β exponents considered in the numerical model by CDS-OpenSees are reported in Table.2, these values are indicated by FIP-Industriale (2013).

Table 2. Numerical parameters of DCFP selected on the basic of controlled-displacement test results.

Surfaces condition	$k_{i,slow}$ [kN/m]	μ_{slow} [%]	$k_{i,fast}$ [kN/m]	μ_{fast} [%]	α [s/m]	β [s/m]
Lubricated (SL)	5000	2.5	400	5	5.0	-0.83
Plus (SNL)	5000	5	400	8	5.0	-0.56

Shaking Table Test

Two experimental configurations have been considered in this paper: i) configuration MC-SNL with centred mass and not-lubricated surfaces (μ_{slow} = 5%; μ_{fast} = 8%); ii) configuration MC-SL with centred masses and lubricated surfaces (μ_{slow} = 2.5%; μ_{fast} = 5%). This paper refers of one-directional shaking table testing considering two natural earthquakes selected from European Strong Motion Database compatible with soil type A (PGA = 0.25g) and soil type B (PGA = 0.45g). In Table.3 the main characteristics and the reference PGA of the seismic inputs are reported. To ensure consistency with the scale of the experimental model, all acceleration profiles were scaled down in duration by a factor of $1/(1.3)^{1/2}$. The normalized elastic spectra of accelerations and of displacements are reported in Fig.5 compared with the design spectrum given by the code (EC8-1, 2004) for soil type A. During testing the PGA was increased in percentage of reference PGA (PGA ref, see Table.3). More detail of complete test programme and major experimental results can be found in Ponzo et al. (2014).

Table 3. Seismic inputs for experimental testing considered in this paper

Waveform ID	Earthquake Name	Date	Mw	PGA ref. [ag/g]	Soil class
287	Campano Lucano	23/11/1980	6.9	0.25	A
196	Montenegro	15/04/1979	6.9	0.45	B

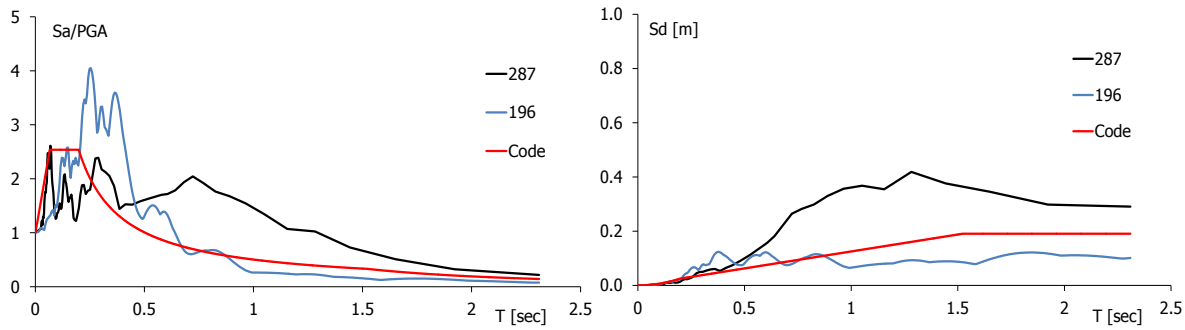


Figure 7: Seismic inputs normalized elastic spectra of acceleration *Sa* and displacements *Sd*

In Fig.8 the experimental values of initial displacements, maximum displacements and residual displacements of the base isolation system are reported. In case of MC-SNL configuration the isolation system responded in a different manner with and without initial residual displacements, but similar maximum displacements were reached. Applying the lubrication (MC-SL configuration), the displacement of the isolation system increased of about 10% and no residual displacements were recorded.

Fig.9 displays the shaking table test results in terms of base displacement history MC-SNL and MC-SL model configurations when accelerograms 287 and 196 with intensity level of 200% (PGA = 0.5g and PGA = 0.9g respectively) were applied. For MC-SNL case the test was repeated resetting the initial residual displacement (configuration indicated with * in Table.3). Both constant and variable

friction models of DCFP show a good agreement with shaking table results when the initial displacement starts from zero.

Fig.s 10 show movement of the DCFP in the vertical plane (YZ) and horizontal (YX) insulator for MC-SNL and MC-SL test configurations considering accelerograms 287 and 196 at PGA=200%. From the figures of the displacement in the vertical plane can be observed the curvature equivalent devices and absence of irregularities related to potential effects of static friction.

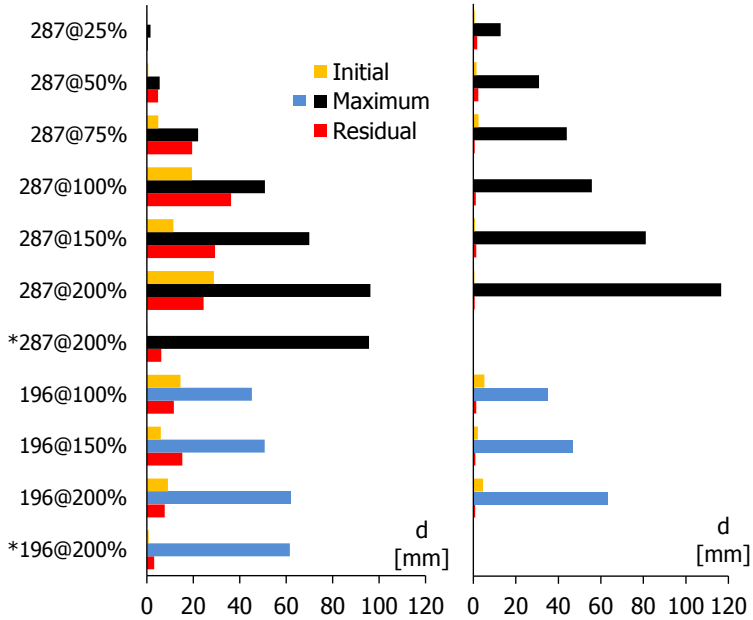


Figure 8: Comparisons between initial, maximum and residual base displacements from the experimental test configurations: MC-SNL and MC-SL.

Results of Numerical Simulations

Fig. 11 and 12 shows the base displacements obtained from experimental tests considering the inputs 287 and 196 at PGA = 200%, for configurations MC-SNL and MC-SL, compared with the results obtained by the numerical analysis with SAP2000 and with CSD-OpenSees, respectively. From Fig.11 a good agreement with the experimental results for both velocity dependence models is shown. Also from Fig.12 a good agreement with the experimental results can be observe only for both axial load dependence models is shown.

In order to better understand the influence of the residual displacement due to previous experimental tests further nonlinear time history analysis have been carried out considering the MC-SNL configuration imposing initial offsets to the SAP 2000 model with constant friction. Fig.13 displays the shaking table test results in terms of base displacement history with inputs 287 and 196 with PGA = 200% with and without initial residual displacement (see Fig.8). The displacement history of the numerical model with offset shows a trend versus experimental results without initial offset. More realistic numerical modelling is required in order to improve the reliability to predict the seismic response also when initial offset are applied to the DCFP isolation system.

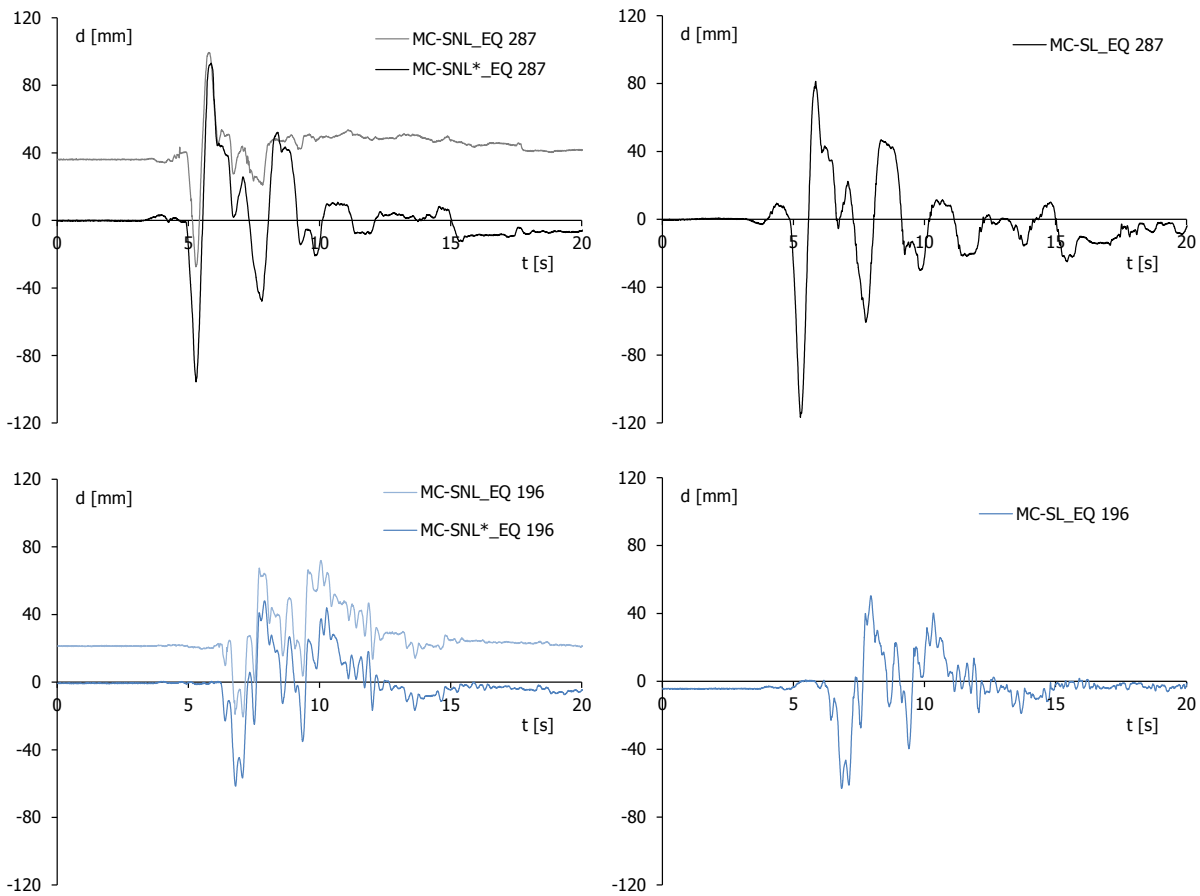


Figure 9: Comparison between experimental test for accelerograms 287 and 196 (PGA = 200%) for model configuration MC-SNL, with and without initial displacement, and MC-SL.

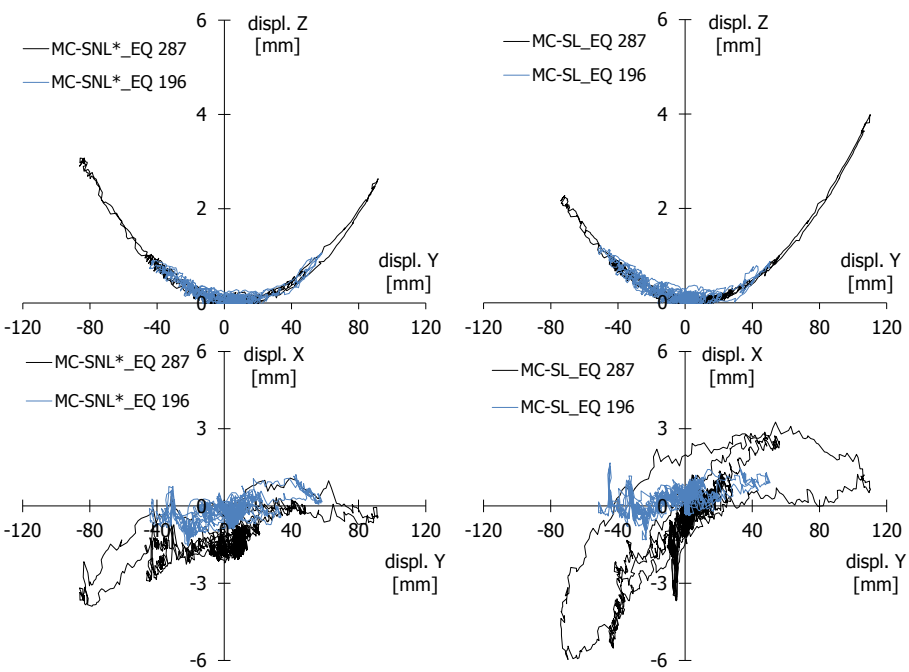


Figure 10: Experimental displacement of the isolation system in the vertical and the horizontal plan for accelerograms 287 and 196 (PGA = 200%) for model configuration MC-SNL, without initial offset, and MC-SL

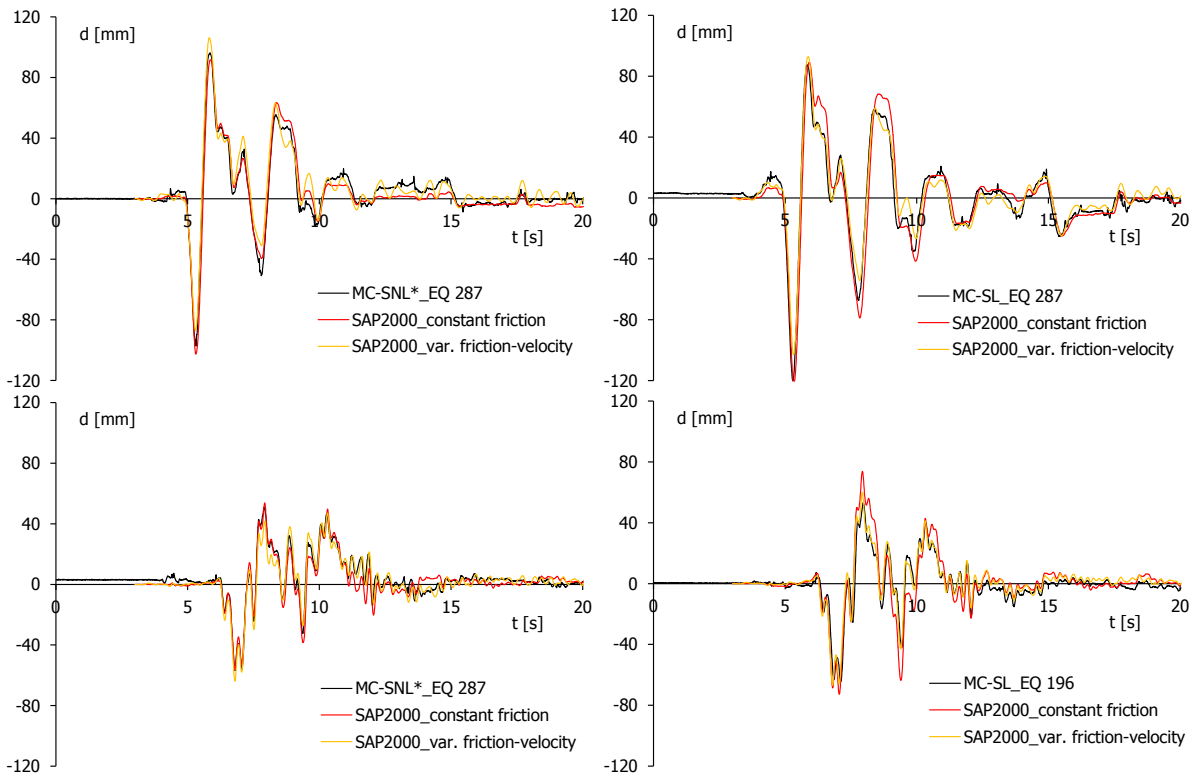


Figure 11: Comparison between experimental and numerical results with SAP2000 for accelerograms 287 and 196 (PGA = 200%) for model configuration MC-SNL, without initial displacement, and MC-SL.

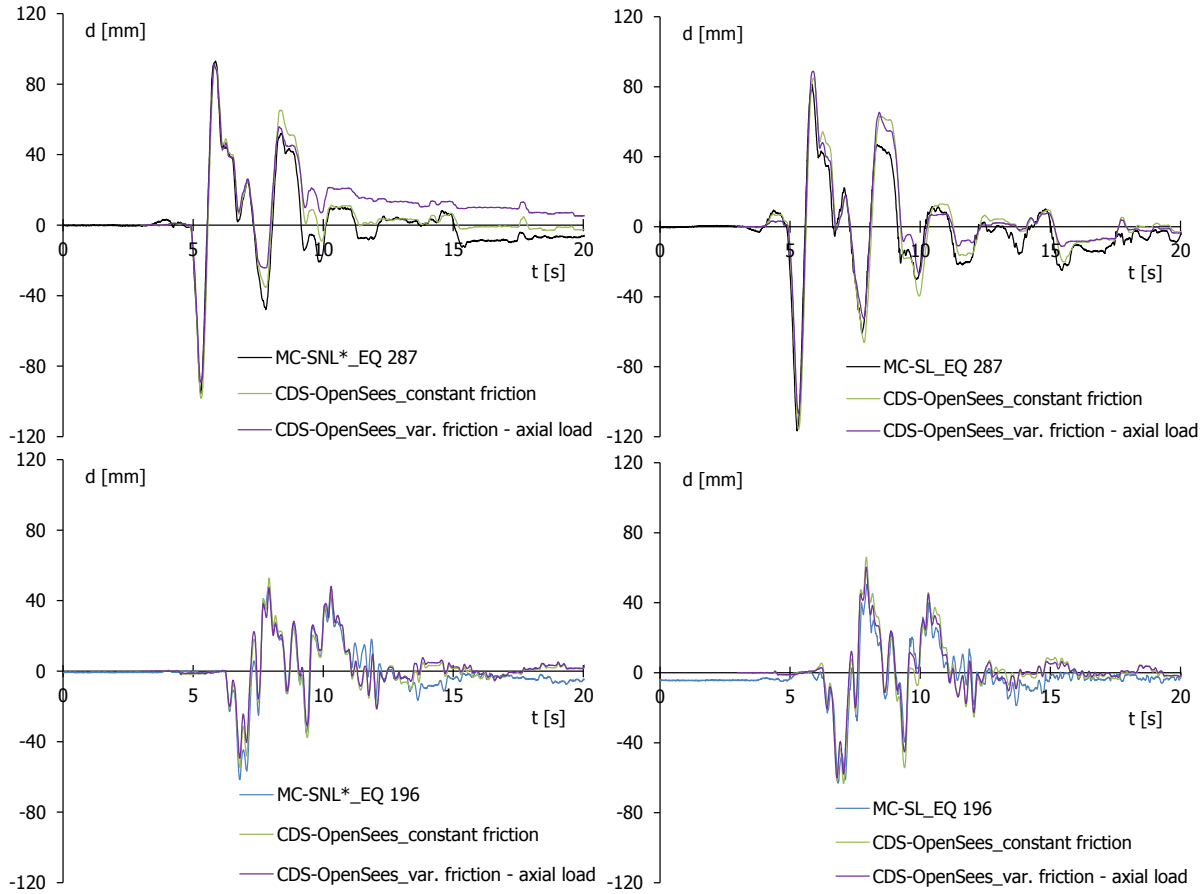


Figure 12: Comparison between experimental and numerical results with CDS-OpenSees for accelerograms 287 and 196 (PGA = 200%) for model configuration MC-SNL, without initial displacement, and MC-SL.

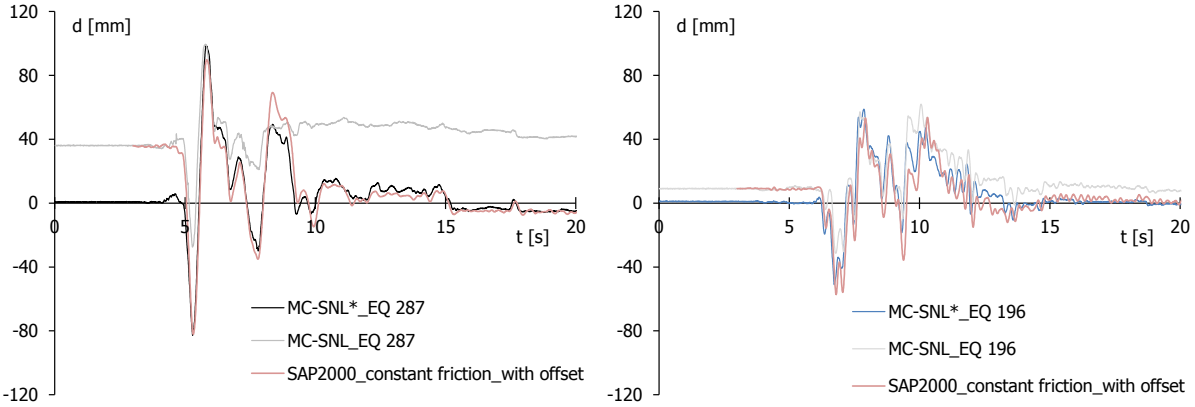


Figure 13: Comparison between experimental and numerical results with SAP2000 for accelerograms 287 and 196 (PGA = 200%) for model configuration MC-SNL with and without initial displacement.

CONCLUSIONS

In this paper double concave friction pendulum (DCFP) with rigid slider and equal radii of curvature have been investigated.

The DCFP bearing were tested under both controlled-displacement and earthquake ground motions. The force–displacement relationship was verified through characterization testing of bearings with sliding surfaces having same friction coefficient and different conditions of lubrication. This paper refers of shaking table test considering the configuration of the test model with symmetric mass, two different sliding conditions (with and without lubrication) and two different seismic inputs. The earthquake ground motion experiments shown that the dynamic behaviour of DCFP bearings is both reliable and repeatable even when initial slider offsets are present, showing stable behaviour under all testing.

The numerical simulations have been performed using two different finite element programme SAP2000 and CDS-OpenSees. In SAP2000 two models of the isolator with definition of friction coefficient by constant or variable with sliding velocity, while in CDS-OpenSees two models of the isolator with definition of friction coefficient by constant or variable with applied axial load.

Both numerical models show similar behaviour to the experimental results in term of displacement history of a DCFP bearing in a strong earthquake. The peaks of bearing displacement experimentally observed were generally estimated with sufficient accuracy (within 10% error) also by mean of constant coefficient models. The model with variable friction coefficient depending on velocity of sliding offered some improvement in the displacement prediction relative to a constant friction model. On the contrary, the model with variable friction coefficient depending on vertical axial load did not shown improvement respect to a constant friction model. The friction coefficient has responded constantly also for significant change of applied vertical load respect the maximum designed (N_{sd} / N_{Ed} = 0.64). Further studies are needed to improve the reliability to predict the seismic response also when initial offset are present and to determine if these conclusions are generally applicable for standard size bearings.

ACKNOWLEDGEMENTS

This work was funded by the Italian Department of Civil Protection within the project RELUIS II-Task 2.3.2 and RELUIS III-Line 6. FIP Industriale, Italy, supplied the DCFP devices. This support is gratefully acknowledged.

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