



RE-CENTRING CAPABILITY OF FRICTION PENDULUM SYSTEM: EXPERIMENTAL INVESTIGATION

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ABSTRACT

In this paper the re-centring capability of the Friction Pendulum System (FPS) is investigated in shake table tests carried out on a steel frame mock up. FPS prototypes with different coefficient of friction are studied. The response of the isolation system is analysed in terms of residual displacements after the end of the earthquake and accumulation of irreversible displacements during a sequence of successive ground motions. The features of the FPS that ensure sufficient re-centring capability are identified.

INTRODUCTION

The re-centring capability is identified by the current design codes as a fundamental requirement of seismic isolation systems. Systems with sufficient re-centring capability demonstrate a tendency to return towards the origin during the seismic event, while a poor re-centring capability generally results in (i) substantial residual displacements after the end of the ground motion, (ii) accumulation of displacements during a sequence of seismic events and (iii) increased maximum and residual displacements for input motions with directivity effects, like e.g. one-side pulse, etc. (Katsaras et al., 2008). Low re-centring capability may result, in certain cases of earthquake attack, to serious damage and even structural collapse due to excessive cumulative displacements. The purpose of the re-centring capability requirement is not so much that of limiting residual displacement at the end of a seismic event, but instead that of preventing cumulative displacements during the event. Re-centring assumes particular relevance in structures located in close proximity to a fault, where earthquakes characterized by highly asymmetric time histories are expected.

In spite of its recognized importance, to date the re-centring capability of seismic isolation systems has been studied by a very few authors. Based on energy concepts, Medeot (2004) formulated the re-centring criterion $E_S \geq 0.25 \cdot E_H$ where E_S is the elastic energy reversibly stored in the isolation system and E_H is the hysteretic dissipated energy. Katsaras et al. (2008) based on theoretical considerations concluded that the re-centring capability of bilinear hysteretic seismic isolation systems depends on both the characteristics of the ground motion excitation and the features of the isolation system, and that the governing parameter is the ratio d_{\max}/d_{rm} , where d_{\max} is the maximum seismic displacement, and d_{rm} is the “static residual displacement” as defined in Eurocode 8 Part 2 (CEN, 2005), i.e. the residual displacement where static equilibrium is reached when the system is unloaded

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under quasi-static condition from its displacement capacity d_{\max} . The Authors undertook a parametric study on a single degree-of-freedom model and demonstrated, from the statistical analysis of the response to 122 different ground motion histories, that bilinear systems with $d_{\max}/d_{\text{rm}} \geq 0.5$ exhibit small residual displacements at the end of the earthquake. The numerical predictions are in line with the results of shaking table tests performed by Tsopelas et al. (1994), demonstrating that isolation systems consisting of sliding bearings, rubber devices and fluid dampers exhibit sufficient restoring force capability when the ratio of characteristic strength (at high velocity) to peak restoring force is less or equal to 3, which is equivalent to $d_{\max}/d_{\text{rm}} > 0.33$. A parametric investigation focused on “flag-shaped” seismic isolation systems (e.g. systems deriving from the combination of flat steel-PTFE sliding bearings with auxiliary re-centring devices based on the superelastic properties of shape memory alloys) was presented by Cardone (2012); on the basis of an extensive study considering more than 300 different parameter combinations and 50 ground motions and following regression analysis, Cardone proposed that an adequate re-centring capability of “flag-shaped” hysteretic isolation systems is guaranteed when $d_{\max}/d_{\text{rm}} \geq 3$.

A seismic isolation system that has increased its popularity worldwide in the last years is the Friction Pendulum System (FPS). The behaviour of the FPS can be described by a bilinear hysteretic model (Fig. 1) with characteristic strength $Q = \mu \cdot W$, yield displacement d_y and post-yield stiffness $K_2 = W/R$, where W is the vertical load, μ is the equivalent coefficient of friction and R is the equivalent radius of the curved surfaces. The re-centring capability of the FPS at a given displacement d is therefore defined from the balance of the restoring force $K_2 \cdot d$ due to the concave sliding surface, that always acts towards the origin, and the friction force $\mu \cdot W$ that can act away from the origin. The static residual displacement d_{rm} where the equilibrium of the latter two forces is reached is equal to

$$d_{\text{rm}} = \frac{Q}{K_2} = \mu \cdot R \quad (1)$$

For the FPS, the re-centring criterion based on the ratio (d_{\max}/d_{rm}) then can be expressed as

$$\frac{d_{\max}}{\mu \cdot R} \geq \lambda \quad (2)$$

where $\lambda = 0.5$ according to both the energy criterion proposed by Medeot (2007) and the criterion based on regression analysis proposed by Katsaras et al. (2008), and $\lambda = 3$ adapting the rule proposed by Cardone (2012) to the FPS.

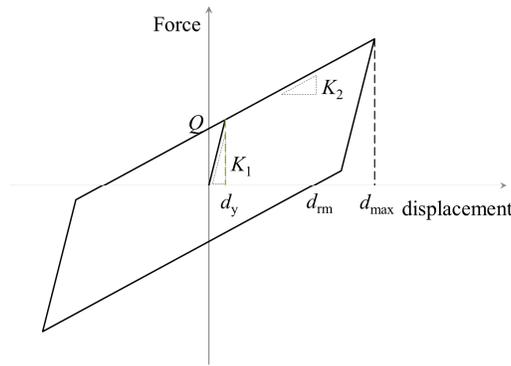


Figure 1. Bilinear hysteretic model of the FPS: Q is the characteristic strength of the isolation system, K_1 and K_2 are the primary and secondary stiffness, d_y is the yield displacement and d_{rm} is the static residual strength.

Re-centring capability criteria have been adopted by modern design codes; however these regulations are in general not based on theoretical fundamentals but on a rather empirical approach and are sometimes questionable: e.g. the criterion $K_2 \cdot d_{\max} \geq 0.25 \cdot W$ proposed in the AASHTO Guide Specifications (2010) is independent of the characteristic strength Q , which appears to be in contrast

with the experimental evidence of poor re-centring behaviour of high friction isolators. A throughout review and evaluation and current codes is presented in Cardone (2012).

An experimental study of the re-centring capability of FPS prototypes was undertaken in an experimental campaign conducted within the national Research Project DPC-ReLUIIS 2010-2013 coordinated by the Italian Department of Civil Protection (DPC) and the Laboratories University Network of seismic engineering (ReLUIIS). The main outcomes are presented in this paper.

SHAKE TABLE TESTS

The shake table tests were carried out on a 3×3 m biaxial shake table at the laboratory of the Department of Structural Engineering of the University “Federico II” of Naples, Italy (but only unidirectional tests were performed in the investigation). The maximum payload of the shake table is 200 kN with a frequency range of 0–50 Hz, acceleration peak equal to 1 g, velocity peak equal to 1 m/s and total displacement equal to 500 mm (± 250 mm).

The mock up is shown in Fig. 2. It was designed as a steel structure at a third-length scale, composed of a vertical frame with dimensions 2.5×2.5 m in plant and 2.9 m height, connected to a rectangular 2.5×2.5 m base frame. The vertical frame was made of welded square hollow columns (cross-section: 150×150×15 mm) of C45 steel material and rolled square hollow beams (cross-section: 120×120×25 mm) of steel S275; the beam-column connections were bolted. The base frame was made of four H-section (HEM160) beams of steel S275, strengthened with horizontal bracings made of steel U-section (UPN80) profiles. The whole structure was supported by four seismic isolation bearings bolted to four rectangular base plates (size 450×610 mm, 50 mm thick) at the corners of the base frame. A reinforced concrete slab (dimensions 2.1×2.65×0.250 m) of class C45/55 was placed on the roof of the structure and a rigid reaction mass consisting of 40 concrete blocks (150×235×305 mm) was placed at the level of the base frame. The total mass of the isolated structure was 8200 kg. Taking advantage of the symmetry of the prototype structure, each isolator supported a quarter of the total weight.

The scale factors of the mock up are summarized in Table 1.



Figure 2. Test mock up.

Table 1. Summary of Scale Factors

quantity	dimension	Scale Factor
Linear Dimension	Length	1/3
Displacement	Length	1/3
Time	Time	1/ $\sqrt{3}$
Mass	Mass	1/9
Velocity	Length \cdot Time ⁻¹	1/ $\sqrt{3}$
Acceleration	Length \cdot Time ⁻²	1
Frequency	Time ⁻¹	3
Force	Mass \cdot Length \cdot Time ⁻²	1/9

Accelerometers and displacement gauges were used to monitor the response of the specimen.

Six triaxial accelerometers PCB Piezotronics model 356A17 (capacity ± 10 g) were installed on the mock up, three at the base level and three at the roof level respectively, at three of the four corners of the structure. An additional accelerometer was placed on the shake table, in order to check the real input transmitted to the specimen.

Laser gages Wenglor CP35MHT80 (capacity ± 150 mm) were used to measure the movements of the structure along two horizontal directions. The gages were arranged as to record the displacements at the corners of the frame at both the base level and the roof level. To complete the instrumentation layout, an additional displacement transducer was used to measure the longitudinal displacement of the table along the direction of motion.

Three isolation layout, each one comprised of four identical FPS bearings, were assessed in the tests. Three different models of FPS bearings were accounted for (Table 2).

Table 2. FPS specimens: pad material and manufacturing details

FPS model	pad material	R_1 (mm)	R_2 (mm)	h (mm)	contact area (mm ²)	bearing pressure (MPa)
LF	lubricated PTFE	770	770	55	60	7.10
MF	lubricated PTFE-bronze compound	770	770	55	60	7.10
HF	PTFE-bronze compound	1270	300	70	80	3.98

Low Friction (LF) and Medium Friction (MF) specimens consisted of double FPS bearings, each one including two pairs of curved surfaces with identical radius $R_1 = R_2 = 770$ mm and a slider with height $h = 55$ mm, corresponding to an equivalent radius $R = R_1 + R_2 - h = 1475$ mm (Fenz and Constantinoou, 2006). The two models differed for the material of the sliding pads: lubricated virgin PTFE resin was used for the Low Friction specimens, and a PTFE – bronze compound lubricated with silicon grease was used for the Medium Friction specimens. The High Friction (HF) model consisted of a single FPS, with radius of curvature of the primary curved surfaces $R_1 = 1270$ mm and radius of the secondary surfaces $R_2 = 300$ mm; the height of the slider was $h = 70$ mm, corresponding to an equivalent radius $R = 1500$ mm. The sliding pad was made of the same PTFE – bronze compound used for the MF model, but not lubricated.

The identification of the coefficient of friction of each FPS model was conducted before testing the isolation layout, by applying to the base of the shake table a unidirectional harmonic drive motion with predefined amplitude (± 50 mm) and increasing frequency from 0.2 to 1.2 Hz. The equivalent coefficient of friction was calculated in correspondence of the resonance frequency as the energy dissipated per cycle divided by two times the product of the supported weight and the total displacement of the isolator.

Table 3 reports the properties of the FPS specimens pertaining to its hysteretic force-displacement behaviour, based on a vertical load of 20.11 kN.

Table 3. FPS specimens: hysteretic loop properties

FPS model	equivalent radius R (m)	coefficient of friction μ (-)	characteristic strength Q (kN)	restoring stiffness K_2 (kN/m)	residual displacement $d_{rm} = \mu \cdot R$ (m)
LF	1.485	0.03	0.603	13.54	0.045
MF	1.485	0.08	1.608	13.54	0.134
HF	1.500	0.12	2.412	13.41	0.188

The design spectrum was calculated in conformity to the current Italian Building Code (NTC, 2008) using the software Rexel v. 3.4 (Iervolino et al., 2010) and upon the following assumptions: structure located at the coordinates of Naples (Longitude 14.2767°, Latitude 40.863°), soil class A and topographic category T1 (corresponding to a ground acceleration of 0.259 g), nominal life of the structure 100 years, life safety limit state (SLV), return period 1898 years and damping ratio 5%.

A set of seven accelerograms, used as input for the shake table, were specifically selected from the European Strong-Motion Database (Ambraseys et al., 2002) so that their average spectrum matched the design spectrum within a $\pm 10\%$ margin over the frequency range from 0.5 to 4.0 Hz (Fig. 3). The selected ground motions are listed in Table 4. Their histories featured magnitude between 5.3 and 7.3 Mw and epicentral distance less than 80 km. Every ground motion record was compressed in time by a factor of $\sqrt{3}$ to satisfy the similitude requirements and scaled to the design ground acceleration level of 0.259 g.

Table 4. Ground motions used in the test program and relevant characteristics

Earthquake name	Earthquake ID	Waveform ID	Station ID	Magnitude (Mw)	Fault mechanism	Epicentral distance (km)	PGA (m/s^2)	Scale Factor
Bingol	2309	7142	ST539	6.3	strike slip	14	2.9178	0.8726
Friuli	34	55	ST20	6.5	Thrust	23	3.4985	0.7277
Montenegro	93	200	ST68	6.9	Thrust	65	2.5094	1.0146
Etolia	203	428	ST169	5.3	Thrust	23	1.7297	1.4719
Lazio Abruzzo	175	372	ST274	5.9	Normal	68	1.2327	2.0653
Campano Lucano	146	290	ST96	6.9	Normal	32	3.1662	0.8041
Campano Lucano	146	287	ST93	6.9	Normal	23	1.7756	1.4339

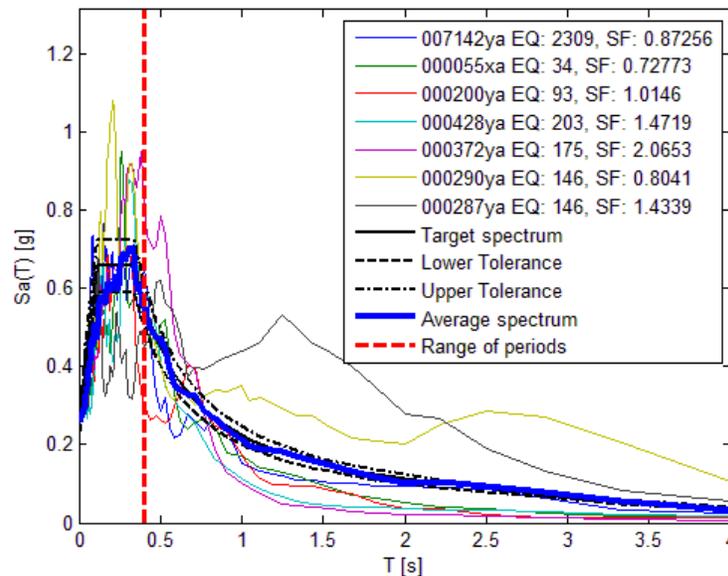


Figure 3. Response spectra (for 5% damping ratio) of the selected ground motions compared to the design spectrum.

Two series of tests were conducted on each isolation layout.

In the first series of tests, the mock up was subjected to the sequence of the seven ground motions. Owing to the symmetry of the prototype structure as well as of the isolation systems, the tests were conducted along only one horizontal direction. Before the application of the ground motion the seismic isolators were checked and adjusted, if necessary, in order to remove any offset.

In the second series of tests, a sequence of three to five successive identical ground motions, corresponding to the time histories 7142 EQ: 2309, 0055 EQ: 34, 0287 EQ: 146 (Fig. 4), was applied. The residual displacement resulting at the end of each earthquake was not removed and represented the initial offset of the isolation system at the start of the next earthquake. Since a series of identical records is examined the analysis corresponds to the unfavourable event in which the residual

displacement of each earthquake is additive to the accumulated residual displacement of the previous earthquakes.

During the tests the horizontal displacements of the test frame at the base and roof levels, as well as the displacements of the table were recorded and used to derive relative displacement histories. The peak displacement (d_{\max}) and the residual displacement (d_{res}) at the base level at the end of each ground motion input were calculated and stored for further analyses.

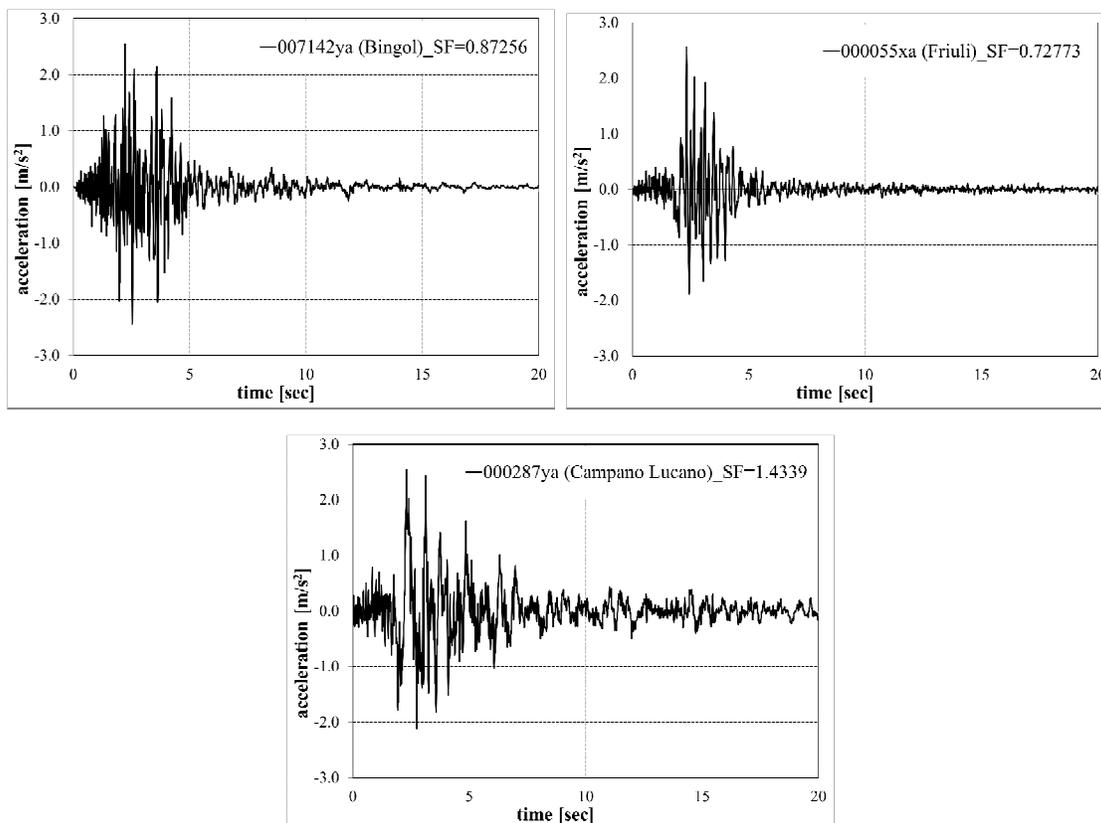


Figure 4. Acceleration time histories used to build the sequences of identical ground motions, scaled to $\text{PGA} = 0.259 \text{ g}$ ($\text{SF} = \text{Scale Factor}$)

RESULTS

The re-centring capability of the FPS was investigated in terms of: (a) residual displacements after the ground motion, (b) influence of an initial offset of the isolation system on the peak and residual displacements after an earthquake, and (c) accumulation of residual displacements during a sequence of earthquakes.

The results of the first series of tests conducted on the three isolation system layouts and consisting of the application of the complete sequence of seven ground motions is illustrated in Fig. 5. Here the distribution of the residual displacement d_{res} , normalized to the peak displacement d_{\max} , is reported as a function of the peak displacement d_{\max} normalized to the static residual displacement d_{rm} . The residual displacement is large compared to the peak displacement ($d_{\text{res}}/d_{\max} \geq 0.5$) when d_{\max}/d_{rm} is small (typically less than 0.2), but the entity of the residual displacement d_{res}/d_{\max} has a decreasing trend as the ratio d_{\max}/d_{rm} increases, eventually becoming negligible when d_{\max}/d_{rm} is equal to, or larger than unity. Specifically, for the FPS models assessed in the study d_{res} becomes an insignificant portion of d_{\max} when d_{\max}/d_{rm} is greater than 0.5. It is noted that for each isolation system there is a significant scatter in the observed data which reflects the dependence of the re-centring capability on the characteristics of the ground motion.

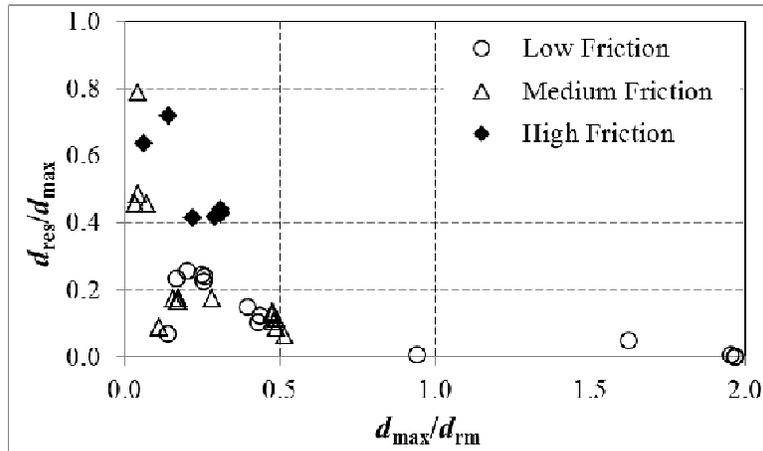


Figure 5. Normalized residual displacement d_{res}/d_{\max} as a function of d_{\max}/d_{rm} for FPS specimens characterized by different coefficients of friction

The residual displacements may accumulate for a series of earthquakes if the isolation system does not possess sufficient re-centring capability. The results of the second series of tests aiming at assessing the build up of residual displacements are illustrated for the three FPS models in Figs. 6, 7 and 8 respectively. The diagrams on the left side of the Figures report the peak (d_{\max}) and residual (d_{res}) displacements for each ground motion of the sequence, while the diagrams on the right side show the courses of the normalised quantities d_{\max}/d_{rm} and d_{res}/d_{\max} .

The dependence of the re-centring capability of the isolation system in terms of accumulation of residual displacements on the normalized peak displacement d_{\max}/d_{rm} is apparent. When d_{\max}/d_{rm} is small, the residual displacement increased after the end of each ground motion, producing a corresponding increase in the peak displacement during the subsequent earthquake, until d_{\max}/d_{rm} exceeds a threshold level (between 0.2 and 0.4 in the study) and the displacement build up comes to an end. On the contrary, when d_{\max}/d_{rm} is large (≥ 0.5) the initial offset tends to be reduced or even eliminated during the seismic event. Here again the scatter in the experimental data that is observed when comparing the responses of the same FPS model to the various time histories is explained as an effect of the characteristics of the individual ground motions, which affects the peak displacement d_{\max} .

DISCUSSION

In this paper, the restoring capability of sliding isolation systems consisting of curved surface sliders, also known as Friction Pendulum System, is investigated in shake table tests in terms of: (a) residual displacements after the ground motion and (b) accumulation of residual displacements during a sequence of earthquakes.

Consistently with similar results presented for typical bilinear hysteretic seismic isolation systems (Katsaras et al., 2008), the main parameter that affects the restoring capability of the FPS is the ratio d_{\max}/d_{rm} , where d_{\max} is the peak seismic displacement and d_{rm} is the maximum residual displacement under which the system can be in static equilibrium. The maximum earthquake displacement d_{\max} includes the effect of the excitation, whereas d_{rm} is a characteristic parameter of the isolation system, independent of the excitation (for a FPS d_{rm} is given by the product of the coefficient of friction and the equivalent radius of curvature). In consequence to this fact, the restoring capability depends not only on the system properties but also on the seismic input. More specifically, for the same FPS the restoring capability is expected on average to be relatively better for seismic motions involving larger displacements than for weaker small displacement motions. For the FPS models considered in the study excellent restoring capability is attained when $d_{\max}/d_{\text{rm}} \geq 0.5$.

From Fig. 5 is also noted that when d_{\max}/d_{rm} is larger than the unity the normalized residual displacement d_{res}/d_{\max} is close to zero and practically independent of d_{\max}/d_{rm} . Though the conclusion is

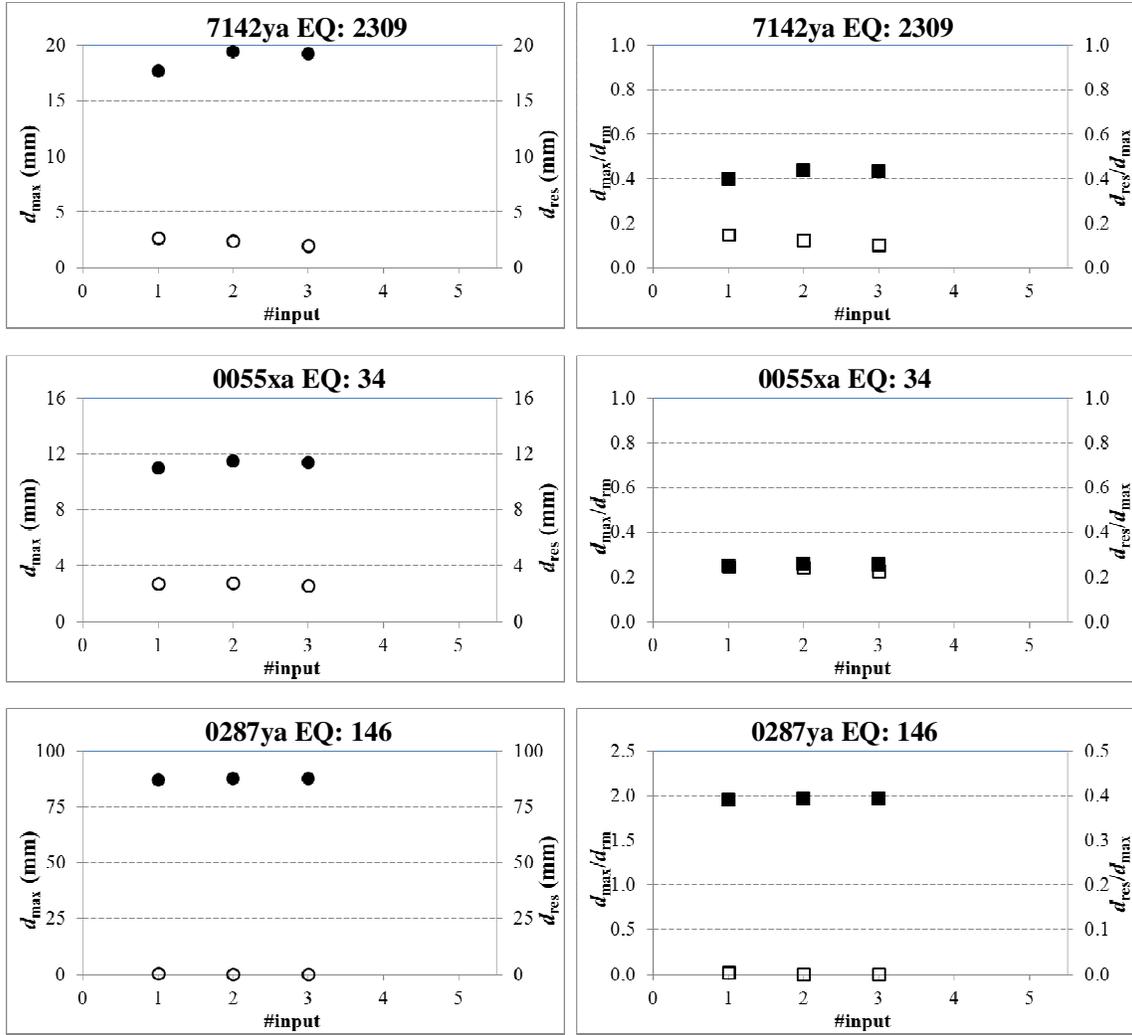


Figure 6. Low Friction FPS specimens: accumulation of maximum and residual displacements during three sequences of successive identical ground motions. Left diagrams: solid circle (●) = d_{\max} , empty circle (○) = d_{res} . Right diagrams: solid square (■) = d_{\max}/d_{res} , empty square (□) = d_{res}/d_{\max} .

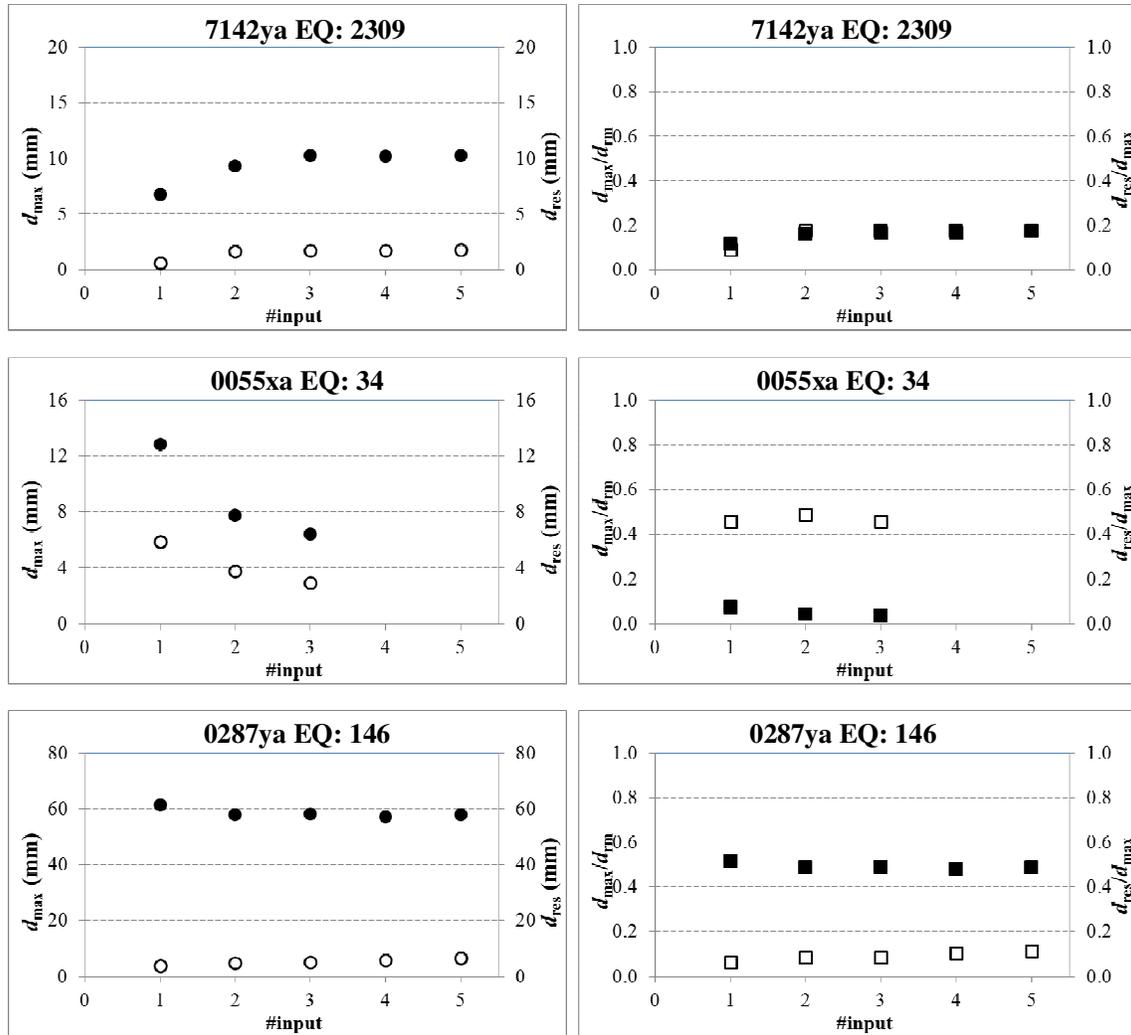


Figure 7. Medium Friction FPS specimens: accumulation of maximum and residual displacements during three sequences of successive identical ground motions. Left diagrams: solid circle (●) = d_{max} , empty circle (○) = d_{res} . Right diagrams: solid square (■) = d_{max}/d_{fm} , empty square (□) = d_{res}/d_{fm}

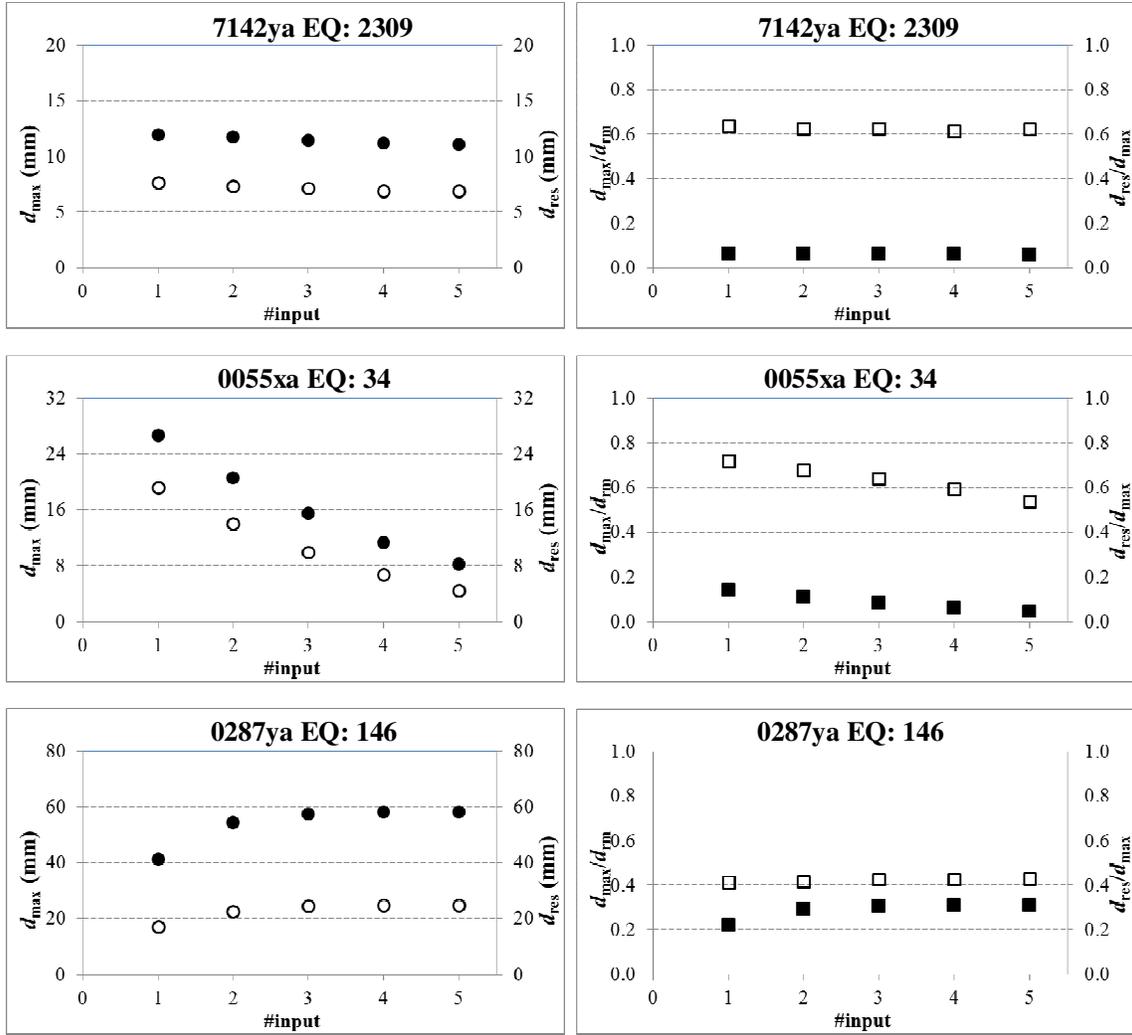


Figure 8. High Friction FPS specimens: accumulation of maximum and residual displacements during three sequences of successive identical ground motions. Left diagrams: solid circle (●) = d_{max} , empty circle (○) = d_{res} . Right diagrams: solid square (■) = d_{max}/d_{fm} , empty square (□) = d_{res}/d_{max}

based only on a small number of tests and needs to be confirmed by a more extensive experimental campaign, this suggests that the design value of the residual displacement d_{res} is the same for every earthquake that induces maximum displacement d_{max} greater than d_{rm} . In these cases the residual displacement is small compared with d_{rm} and not sensitive with respect to the increase in the maximum displacement of the isolation system.

The analysis of the response of the isolation systems to a sequence of successive identical ground motions provides consistent results (Figs. 6, 7 and 8) and demonstrates that isolation systems with $d_{max}/d_{rm} \geq 0.5$ have excellent re-centring performance in terms of both negligible accumulation of residual displacements and elimination of an initial off-set of the isolation system during the strong-motion. Comparing this outcome to previous literature, one can find in the presented study an experimental confirmation that the general criterion $d_{max}/d_{rm} \geq 0.5$ formulated for bilinear hysteretic isolation systems (Medeot, 2007; Katsaras et al., 2008) based on parametric analyses of single-degree-of-freedom systems keeps validity even when applied to evaluating the re-centring capability of FPS isolators.

For the Friction Pendulum System, the maximum seismic displacement normalized to the static residual displacement d_{max}/d_{rm} has a precise mechanical interpretation in terms of comparison between restoring and hysteretic forces. The property d_{max}/d_{rm} can be expressed indeed as $K_2 \cdot d_{max}/Q$, where K_2 and Q are illustrated in Fig. 1. Therefore, the criterion $d_{max}/d_{rm} \geq 0.5$ is equivalent to require that the ratio of the increment of the post-yield force between displacements 0 and d_{max} , which increases the re-centring capability, is at least half of the characteristic strength Q which is related to friction forces that induce imperfect re-centring.

CONCLUSIONS

A simple and representative parameter that can be used to characterize the re-centring capability of the Friction Pendulum System is the ratio d_{max}/d_{rm} . The quantity d_{max} includes the effect of the ground motion excitation, while d_{res} is a parameter of the isolation system (specifically for the FPS, d_{res} is the product of the equivalent radius and the coefficient of friction of the curved surfaces) independent of the earthquake. The re-centring capability is larger for seismic motions involving larger displacements than for weaker small displacement motions.

The shake table tests presented in this study suggest that systems with d_{max}/d_{rm} greater than 0.5 demonstrate excellent restoring capability, though this needs to be confirmed in a more extensive experimental campaign.

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