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COMPARISON OF THE EXPERIMENTAL RESPONSE OF CURVED AND FLAT SLIDING MOTIONS

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ABSTRACT

Research activity on Concave Surface Slider devices has grown exponentially in last decades. Frictional response leads to high values of dissipated energy during a seismic event, so that a significant reduction of both displacement and force demands can be experienced by the base-isolated structural system. On the other hand, several issues have been pointed out thanks to the outcomes of experimental campaigns, carried out on full-scale isolators. Precisely, frictional properties can be defined as a function of some response parameters, such as sliding velocity, vertical load and dissipated energy. Generally, these dependences are evaluated by computing the average friction coefficient per cycle of static and dynamic tests, by assuming the lateral response of full-scale device as the direct summation of the frictional force and the recentering contribution, in terms of linear elastic response. However, no direct comparison between the response of a Curved Surface Slider response and the experimental frictional response of the corresponding flat sliding material can be found in the literature.
In this endeavor the experimental response of full-scale flat and curved sliding devices have been directly compared. Time series of lateral force of Concave Surface Slider isolators have been overlapped to hybrid signals: such signals are returned by the summation of the experimental frictional response of a flat slider, which has the same pad diameter of the studied isolator, and a numerical linear recentering force. Results have shown a fairly good agreement between the experimental behavior of Curved Surface Slider and the Hybrid force obtained from the frictional flat response.

Keywords: Friction coefficient; Curved Surface Slider; Flat slider; Base Isolation

1 INTRODUCTION

Recent advances in experimental investigations on Concave Surface Slider (CSS) devices have led to a better understanding of the overall behavior of such isolators under any conditions of loading. The main dependencies of the friction coefficient with respect to the main response parameters (i.e. sliding velocity, vertical load/contact pressure and cyclic effect) have been studied by testing several sliding materials, commonly used in real practice (Barone et al. 2017, Calvi et al. 2004). Such dependencies can be noticed in the lateral force signals of both flat and curved sliding motions, but the correlation between these different loading conditions still needs to be more and more investigated, for all the velocity, load and cyclic effects (Lomiento et al. 2013, Quaglini et al. 2014, Dolce et al. 2005). Furthermore, the main working condition of a CSS device is considered as the summation of a frictional response (curved sliding motion) and a linear recentering force, by assuming the stiffness coefficient equal to the ratio between the applied vertical load and the equivalent radius of curvature (Fenz and Constantinou 2006, Quaglini et al. 2017). Such an assumption has to be validated, according to bidirectional flat and curved motions, which represent the most realistic case for isolation devices, even though two components seismic events can be analyzed as equivalent radial earthquakes (Furinghetti and Pavese, 2017b).
The present study provides the comparison between flat and curved sliding bidirectional motions is provided, thanks to the outcomes of dynamic tests performed at the Laboratory of EUCENTRE

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Foundation in Pavia. Full-scale devices have been investigated, and differences between force responses of a full-scale DCSS device according to both curved and flat motions are studied and commented.

2 TESTED DEVICES

For the presented investigation two individual sliding devices have been adopted. Precisely, full-scale isolators have been considered, in order to get more comprehensive experimental results, as representative of realistic loading conditions (Furinghetti and Pavese, 2017a).
The former device represents the pure frictional behavior: it consists of a stainless steel flat sliding surface, which has been polished to mirror finish, with a roughness index Ra 0.2 and a slider which houses a circular sliding pad. Such a Flat slider can accommodate displacements along all directions up to 250mm.
The latter isolator is a Double Concave Surface Slider. Such a device represents one of the most common technology for isolation bearings: both the curved sliding surfaces have been polished to mirror finish in order to achieve the same roughness index of the Flat Slider, so that same frictional properties can be obtained; moreover, the same radius of curvature has been considered, which implies that the global horizontal motion applied to the device is divided in two equal and opposite sliding motions at the sliding interfaces. Within the equal sliding surfaces, a non-articulated slider is installed, which is made up of a unique steel block (material S355JR): such an element houses two circular sliding pads, having same diameter (260mm) and same material composition, aiming at considering the same contact pressure and the same frictional properties at both the sliding interfaces. Radii of curvature for the sliding surfaces are equal to 1600mm whereas the height of the internal slider is 120mm: these sizes lead to the definition of the equivalent radius of curvature of the device, approximately equal to 3080mm. A maximum vectorial displacement equal to 250mm can be applied to the device along any direction.
In Figure 1 both the considered isolation bearings are shown.

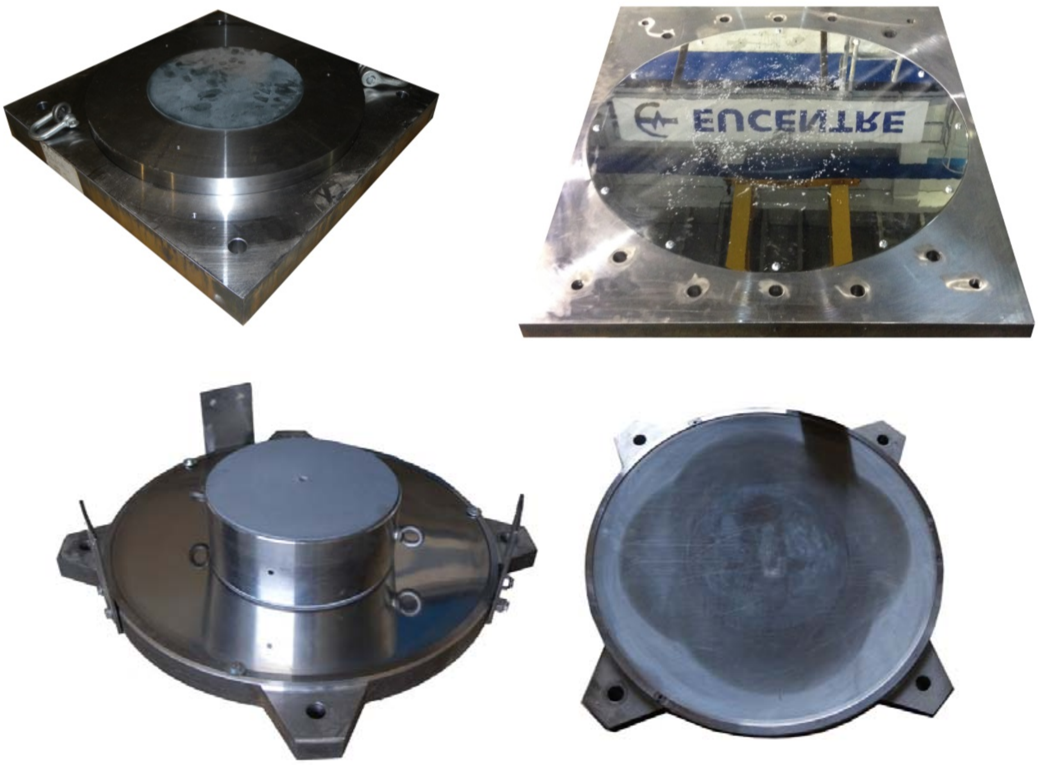

Figure 1. Full-scale Flat (top) & Concave (bottom) Surface Slider devices (FS & DCSS)

An innovative sliding material has been implemented into the studied devices, which consists of a pigmented graded PTFE filled with carbon fibres. Due to the chemical formulation, such a material results in a much stiffer material in comparison to ordinary PTFE compositions.

3 BIDIRECTIONAL TESTING PROTOCOL

Bidirectional tests have been carried out at the Laboratory of the EUCENTRE Foundation in Pavia (Peloso et al. 2012), according to the cloverleaf trajectory ruled by the European standard code UNI:EN15129:2009 for anti-seismic devices (CEN 2009). Cloverleaf orbits can be obtained by applying actual displacement input signals along two orthogonal directions x and y, returned by the summation and multiplication of harmonic functions with different frequencies.

$$\begin{aligned} x(t) &= \frac{D_{max}}{\sqrt{2}} \cdot \sin(4\pi ft) \cdot [\sin(2\pi ft) + \cos(2\pi ft)] \\ y(t) &= \frac{D_{max}}{\sqrt{2}} \cdot \sin(4\pi ft) \cdot [\sin(2\pi ft) - \cos(2\pi ft)] \end{aligned} \tag{1}$$

According to the aforementioned expressions, the peak vectorial velocity of the test can be obtained.

$$V_{max} = 4 \cdot \pi \cdot f \cdot D_{max} \tag{2}$$

During the test, the tangent velocity modulus varies between 50% and 100% of the peak value: such velocity fluctuations may cause additional unexpected discrepancies in the overall frictional behavior of the device. Thus, a special resampling procedure has been applied to all tests, in order to obtain a constant modulus of the tangent velocity for the whole duration of motion. In Figure 2 input signals for both the ordinary and CTV (Constant Tangent Velocity) orbits are compared.

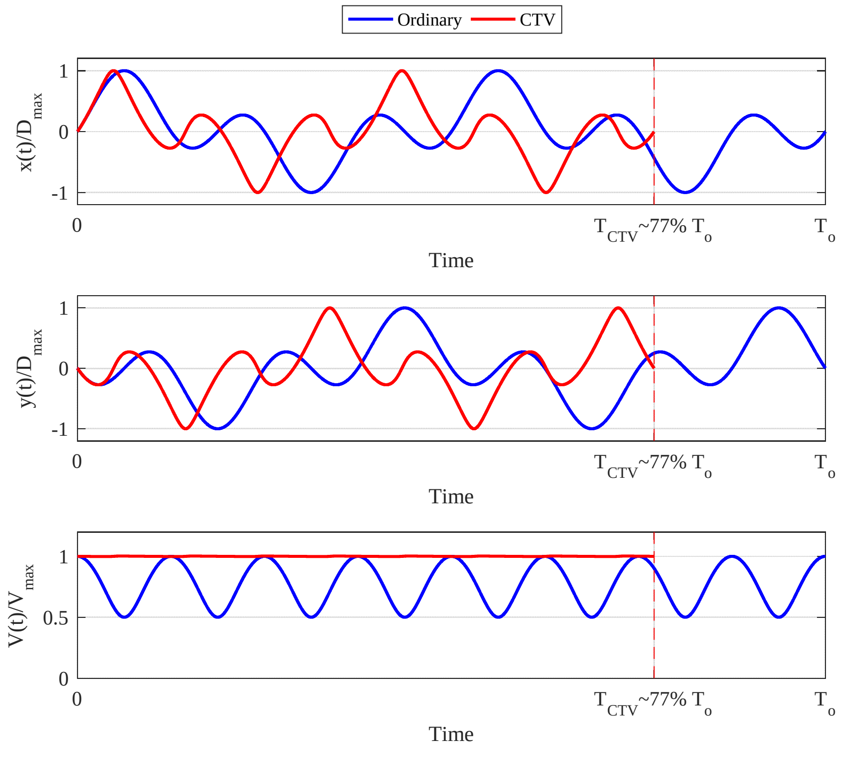

Figure 2. Comparison between ordinary and CTV bidirectional orbits

In Table 1 the testing protocol for the DCSS isolation bearing is listed.
In this work the comparison between flat and curved frictional response of sliding isolators has been investigated, by applying the previously defined bidirectional trajectories to both the Flat and the Curved sliders. In order to make results comparable, a proper scaling procedure has been considered for the testing protocol of the flat device. Precisely, since the Curved Slider has the same radius of curvature for both the sliding surfaces, each sliding interface of the internal slider is subjected to 50% of the global displacement applied to the device; consequently, also the velocity is half of the global value. Hence, the testing protocol of the Flat Slider (FS) is obtained by dividing by 2 peak values for both maximum displacement and velocity.

Table 1. Bidirectional testing protocol for DCSS devices

Test #	**Test Name**	**Max Displ. D_{max} [m]**	**Max Velocity V_{max} [m/s]**	**Vertical Load W [kN] (MPa)**	**Cycles [#]**
1	Cloverleaf – CTV	0.200	0.020	796 (15)	2
2	Cloverleaf – CTV	0.200	0.080	796 (15)	2
3	Cloverleaf – CTV	0.200	0.300	796 (15)	2
4	Cloverleaf – CTV	0.200	0.020	1751 (33)	2
5	Cloverleaf – CTV	0.200	0.080	1751 (33)	2
6	Cloverleaf – CTV	0.200	0.300	1751 (33)	2
7	Cloverleaf – CTV	0.200	0.020	2388 (45)	2
8	Cloverleaf – CTV	0.200	0.080	2388 (45)	2
9	Cloverleaf – CTV	0.200	0.300	2388 (45)	2

In this endeavor, experimental results for the considered sliding material are reported, by applying 15MPa, 33MPa and 45MPa contact pressures, and by considering two repetitions of bidirectional CTV cloverleaf orbit for all tests.

4 DEFINITION OF THE HYBRID FORCE RESPONSE

Generally, the lateral response of a Concave Surface Slider (CSS) device is considered as the direct summation of two individual contributions: the restoring force, provided by the stepwise projection of the applied vertical load along the tangent line to the sliding surface, and the curved frictional force, originated at the sliding interfaces. This work provides a comparison between the experimental behavior of a Curved Slider (CS) and a hybrid response, computed as the summation of an experimental flat frictional force F_{f-Flat}, provided by tests carried out on the Flat Slider, and a numerical recenetring force $F_{rec-num}$, modeled as a linear spring with respect to displacements along x and y directions.

$$F_{Hybrid} = F_{f-Flat} + F_{rec-num} = F_{f-Flat} + \frac{W}{R_{eq}} \begin{bmatrix} x \\ y \end{bmatrix} \tag{3}$$

Thanks to the presented definition of hybrid forces, it is possible to evaluate differences due to both curved rather than flat frictional responses, and the assumption of linear recentering behavior. To this aim, the same diameter of the implemented sliding pads for both the tested devices has been considered, and a proper scaled flat testing protocol has been defined, in order to apply same loading conditions to all the sliding interfaces.

5 EXPERIMENTAL & ANALYTICAL RESULTS

In Figure 3, Figure 4 and Figure 5 results are shown for all the velocity levels, with a contact pressure equal to 15MPa, 33MPa and 45MPa respectively.

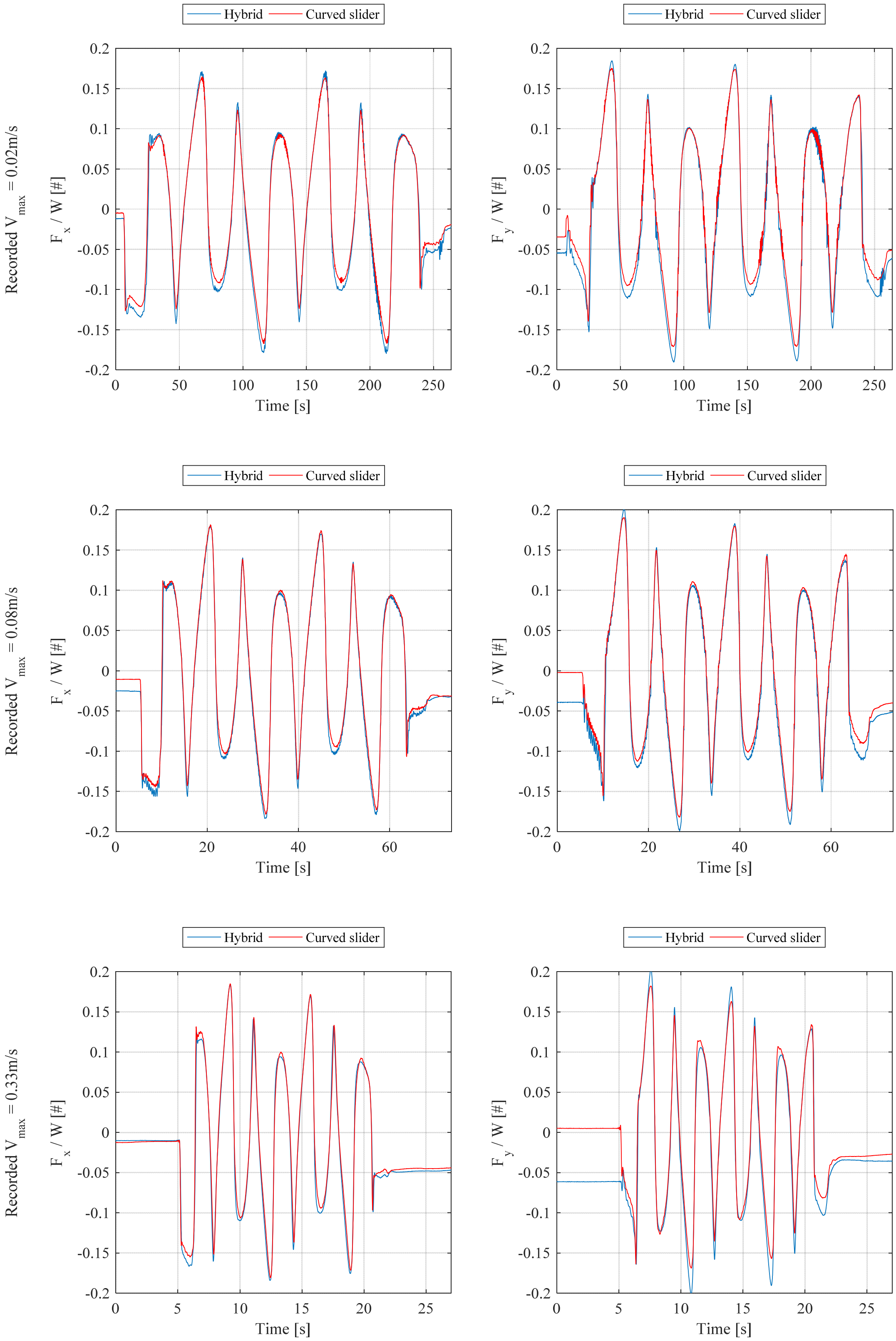

Figure 3. DCSS-D260 (W = 796 kN): Hybrid vs. Experimental CTV orbits response

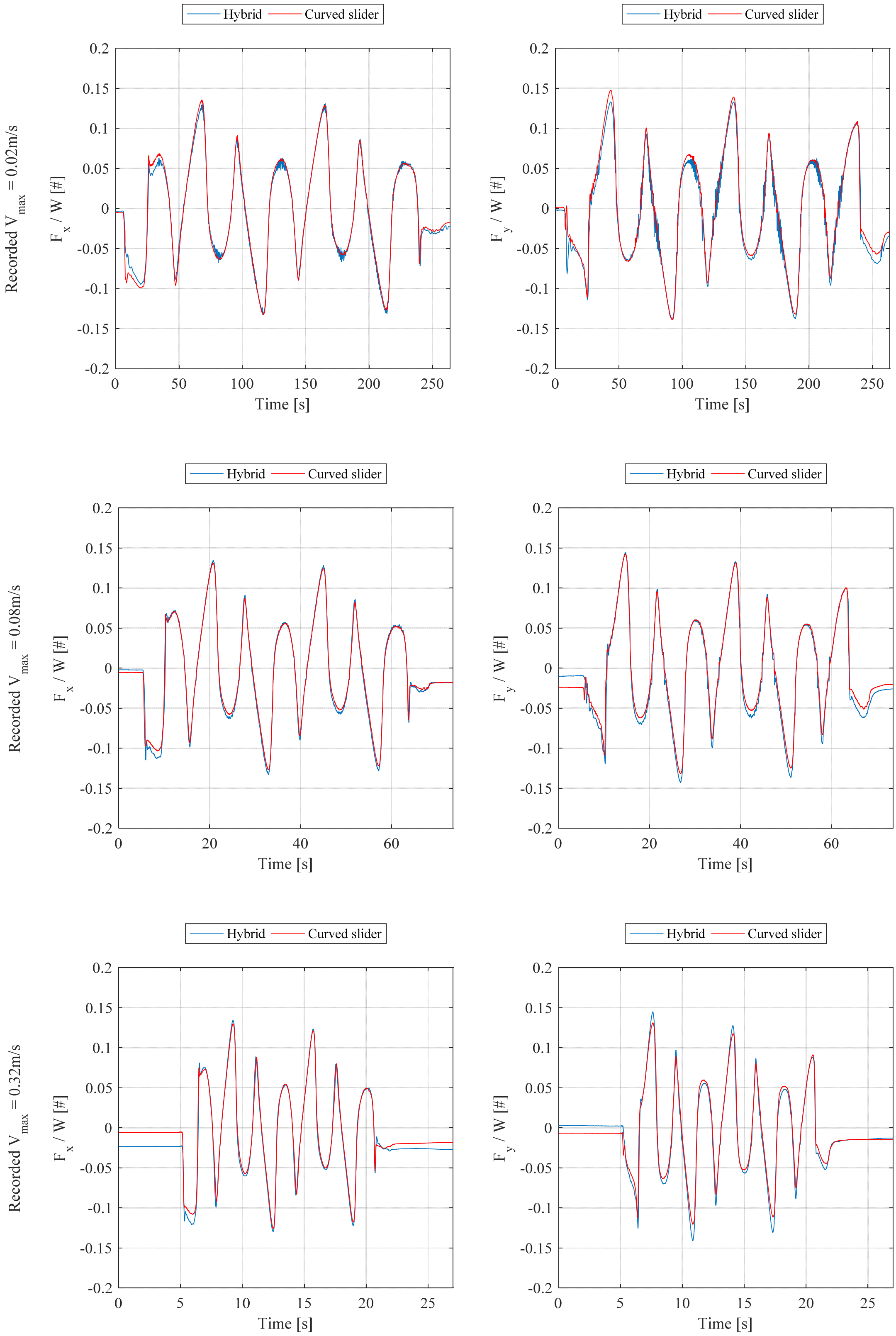

Figure 4. DCSS-D260 (W = 1751 kN): Hybrid vs. Experimental CTV orbits response

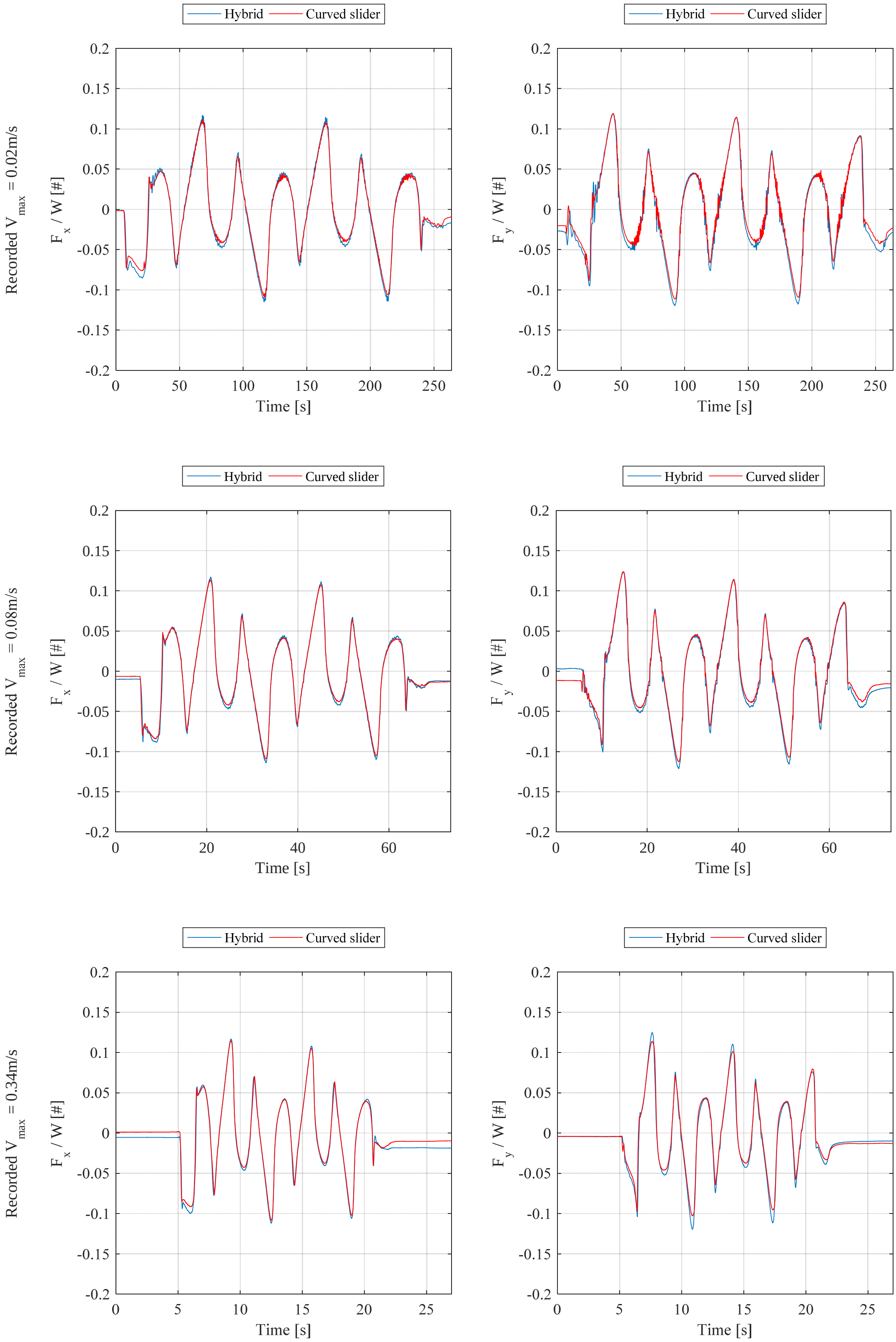

Figure 5. DCSS-D260 (W = 2388 kN): Hybrid vs. Experimental CTV orbits response

Results are previously shown in terms of comparison of force time series, normalized with respect to the applied vertical load W, along x (left) and y (right) directions of motion. It can be noted that the real experimental and the hybrid signals are approximately overlapped for the whole duration of the test and along both directions, under any loading conditions. At some time instants, the hybrid response leads to slightly higher values in comparison to the device experimental force, exception made for test #4 (contact pressure: 33MPa – V_{max} = 0.02m/s), where the opposite behavior can be noticed. The main difference between bidirectional rather than radial motions is represented by the orientation of the frictional force: if the device moves along two individual directions simultaneously, the frictional force can be approximately assumed to be parallel to the applied trajectory, so it is no longer parallel to the recentering force, as happens in the uni-directional case. Thus, since graphical results of force time series have shown a good agreement between the experimental curved and the flat hybrid responses, it can be assessed that flat sliding conditions lead to the same projections of the frictional force of both the curved sliding interfaces of the tested Double Concave Surface Slider device. Furthermore, for the considered geometry, the recentering force can be effectively modeled as a linear spring with respect to displacements along both directions, with a tangent stiffness coefficient equal to the ratio between the applied vertical load and the equivalent radius of curvature of the isolator.
In Figure 6 the agreement between the flat hybrid and the experimental curved responses is analyzed, by comparing total dissipated energy values for both the cases.

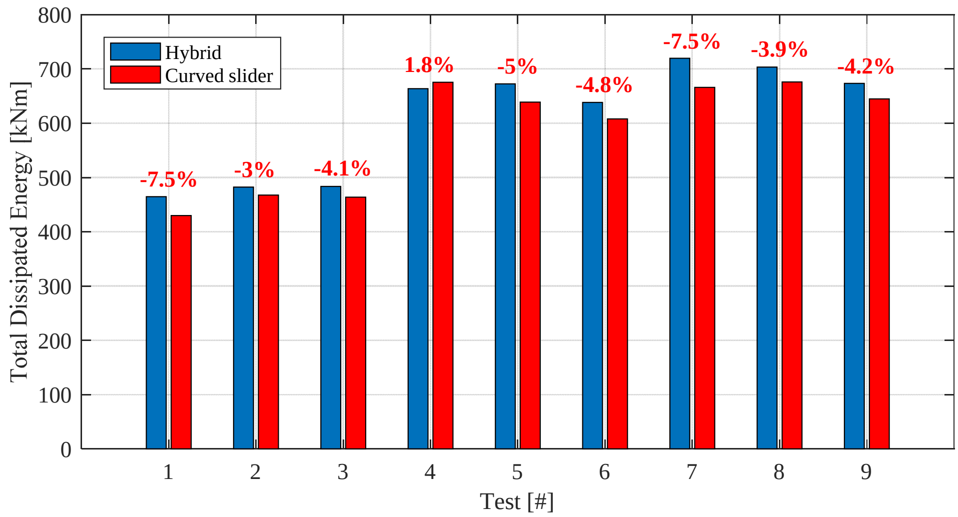

Figure 6. Total dissipated energy comparison

The total dissipated energy has been computed as the time integral of the scalar product between the force and the displacement increment vectors. As can be noticed, also from the dissipative capacity point of view, the hybrid flat response leads to non significant discrepancies, with respect to the real experimental behavior of the considered DCSS device. Generally, negative variation percentages can be found for all the tests, but test #4: this aspect is mainly due to the higher force values associated to the hybrid response, which have been found by analyzing the force time series. As a consequence, hybrid hysteretic loops along both directions have slightly higher areas, and the resulting total dissipated energy is overestimated, in comparison to the real device. The minimum variations are close to -7.5%, and an upper bound equal to +1.8% has been obtained: hence, it can be assessed that for all the considered loading conditions the real device dissipative behavior is well captured by the hybrid composition of the flat experimental frictional force and the numerical recentering response.

6 EARTHQUAKE SIMULATION

In this section results for an earthquake simulation are reported. Precisely, both x and y components of Loma Prieta seismic event occurred on October 18th 1989 have been applied at the base of a bi-directional non-linear Single Degree of Freedom oscillator, in order to obtain displacement input signals for the tested isolator; a constant friction coefficient has been assumed, in agreement with the applied vertical load/contact pressure (μ = 9,4%). Same comparisons between flat and concave sliding motions have been provided for both x and y directions, as previously analyzed for cloverleaf orbits; results are shown in Figure 7.

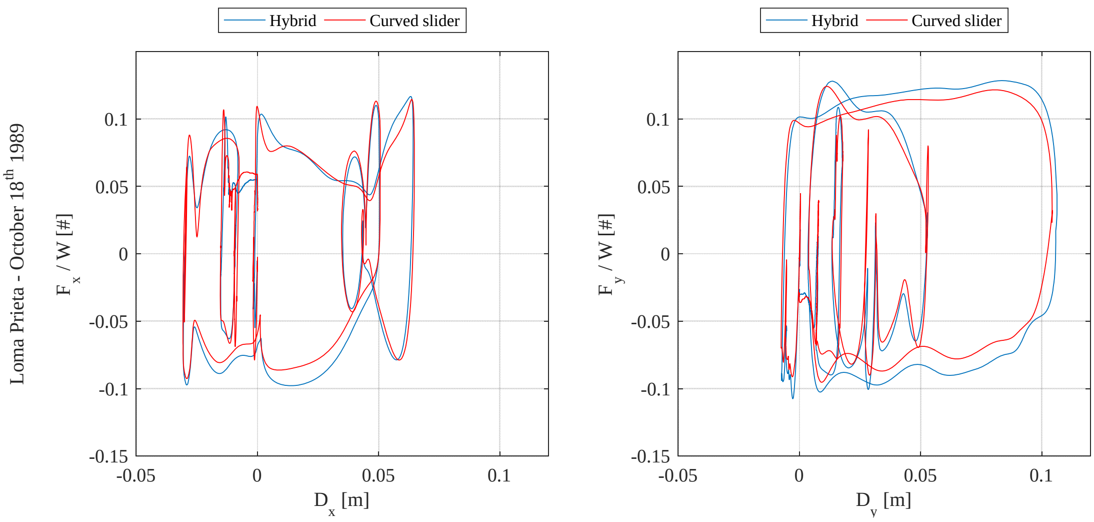

Figure 7. DCSS-D260 (W = 1751 kN): Hybrid vs. Experimental earthquake simulation

As can be noted, hysteretic loops related to curved sliding conditions along both directions of motion can be fairly approximated by the hybrid response, even though a bidirectional seismic event has been considered, and highly non-linear responses have been recorded. Forces values are slightly higher for the hybrid case, that is the composition of the flat frictional force and the numerical recentering contribution; similarly, dissipated energy values are very close one to each other (under flat conditions the dissipated energy is 5,6% more than the returned value by curved sliding motions).

7 CONCLUSIONS

In the present endeavor the comparison between flat and curved sliding motions is investigated. A number of bidirectional dynamic tests have been analyzed, by considering different loading conditions (i.e. contact pressure and sliding velocity). Full-scale devices have been tested, in order to provide results more comparable to real practical implementations. Precisely, a Flat Slider (FS) and a Double Concave Surface Slider (DCSS) have been used for the present study, by considering the same diameter of the sliding pad for all the interfaces. Furthermore, since the radii of curvature of the sliding surfaces of the Curved Slider are equal, 50% of the global displacement of the DCSS isolator is applied to each sliding interfaces, and consequently also the velocity is reduced by the same percentage: thus, in order to make results comparable, the testing protocol for the Flat Slider has been defined according to 50% of the peak displacements and velocities related to the curved device. Both the isolation bearings have been equipped with an innovative sliding material, which consists of a graded PTFE filled with carbon fibres. Bidirectional tests have been carried out, by assuming the cloverleaf orbit, as ruled by the standard code UNI:EN15129:2009 for anti-seismic devices; a special resampling procedure has been applied, in order to obtain a constant tangent velocity modulus for the whole duration of all tests. Flat and Curved sliding conditions have been compared, by defining a

hybrid response, which consists of the experimental frictional force of the Flat Slider device and a numerical recentering force, computed as a linear spring with respect to displacements along reference directions x and y (the tangent stiffness is assumed as the ratio between the applied vertical load and the equivalent radius of curvature). Results have been analyzed by comparing force time series and total dissipated energy values for each test.
The analysis of the force time series shows that flat sliding motions provide a fairly good approximation of the frictional behavior of the DCSS device: experimental and hybrid force signals are almost overlapped at all time instants, under any conditions of loading. The hybrid response seems to lead to slightly higher values of force along both directions, even though small variations can be noticed. This suggests that the recentering behavior can be effectively modeled as a linear spring with respect to displacements, by assuming the stiffness coefficient as the ratio between the applied vertical load and the equivalent radius of curvature. Furthermore, the frictional decay due to the heating phenomena which occur at sliding interfaces is captured by the hybrid response (i.e. the flat sliding motion), especially thanks to the proper scaling procedure of the testing protocol for the flat device. The total dissipated energy of all tests is well approximated by the hybrid composition of the flat experimental response and the numerical recentering behavior. Generally, negative variation percentages are noticed, with respect to the DCSS case, and values averagely bounded between -7.5% and +1.8% have been computed. The same agreement between the investigated flat and concave motions has been noticed under general seismic input, by means of an earthquake simulation.
The presented results seem to highlight that flat sliding motions can represent the actual frictional behaviors which occur in a Concave Surface Slider device under several points of view. Such a conclusion could be very useful, whenever a large Curved Slider device has to be tested: the recentering contribution can be generally equal or even higher than the frictional one, and too high force demands can be achieved for the testing equipment. If it was possible to carry out tests on the flat full-scale sliding pad only, the global response of the CSS device would be computed by defining the hybrid signals along both directions and much lower force values could be experienced. However, results must be further validated by considering different diameters of the sliders, rather than several sliding materials, in order to cover the most common situations of real practice.

8 ACKNOWLEDGMENTS

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