INNOVATIVE MATERIALS FOR THE SEISMIC PROTECTION OF STRUCTURES: FROM RESEARCH TO APPLICATION

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Abstract

In the recent years, the experimental investigation on the frictional response of Curved Surface Sliders (CSS) - the European name for pendulum isolators - has been increased and improved, by performing a lot of full-scale dynamic testing, using facilities of large capabilities. Experimental data allow a better understanding on the dependence of the frictional properties of the sliding material under different loading conditions and velocities. The UHMW-PE (Ultra-High Molecular Weight Poly-Ethylene) is a widely used sliding material for CSS, for the last 10 years, due to its exceptional tribological properties in terms of load bearing capacity, wear resistance, stability and durability. However, limited number of studies are available on the dynamic behaviour of full-scale CSS, equipped with UHMW-PE, investigating the influence of pressure and sliding velocity. This paper presents an investigation of the dependence of friction coefficient on these two parameters by analysing experimental results collected from a number of type tests performed at four dynamic testing facilities (FIP MEC, Italy, SIS Lab, Italy, TREES Lab, Italy and Caltrans SRMD, USA) on full-scale Double Concave Curved Surface Sliders (DCCSS) equipped with the UHMW-PE sliding material. Most of said tests were performed according to the European Standard EN 15129:2009. Eighteen different typologies (thirty-six isolators) were collected, tested at different capacity in terms of vertical load (from 1670 kN to 17500 kN) and seismic displacements ranging from 110 mm to 450 mm. The test velocities range from 250 mm/s to 660 mm/s. The paper presents the results of said tests, as well as some examples of applications of CSS, and in particular DCCSS, in different types of structures.

1 INTRODUCTION

It is well known that the pendulum isolators, or Curved Surface Sliders (CSS) according to the definition of the European Standard EN 15129:2009, are sliding isolators based on the working principle of the simple pendulum, in which the period of oscillation does not depend on the mass but on the length of the pendulum. In a structure isolated with curved surface sliders, the period of oscillation mainly depends on the radius of curvature of the curved sliding surface. The energy dissipation is provided by friction due to movement in the sliding surface, and the re-centring capability is provided by the curvature of the sliding surface.

After the USA's patent expired, the manufacturing of this type of isolators started in many other countries, including Europe as well as Italy. Consequently, the number of structures isolated with these isolators increased. FIP has manufactured more than 17000 CSS from 2009 to 2018, installed in different types of structures (buildings, bridges, tanks, etc.) in 14 different countries. Some examples of applications are reported in [1], [2], [3], [4], [5], [6].

2 CURVED SURFACE SLIDERS

There are two main types of curved surface sliders, which may be simple (CSS) or double concave curved surface units (DCCSS). CSS has a main sliding surface that accommodates the horizontal displacement, provides restoring force and energy dissipation through friction, and a secondary sliding surface aimed at accommodating rotations only (Figure 1 left). DCCSS comprises two facing primary sliding surfaces with the same radius of curvature, both contributing to the accommodation of horizontal displacements and rotation, as well as restoring force and energy dissipation (Figure 1 right). In this case each single sliding surface is designed to accommodate only half of the total horizontal displacement, so that the dimensions in plan of the DCCSS devices may be significantly smaller compared to the CSS devices, for the same vertical load and horizontal displacement capacity.

Figure 1: Scheme of a CSS (left) or DCCSS (right).

As stated above, the law of the simple pendulum is the functional law of both types of curved surface sliders (CSS or DCCSS), where the length of the pendulum corresponds to the radius R of the curved sliding surface (or the equivalent radius for DCCSS). Analogously, the effective fundamental period (T_e) of the isolated structure with these isolators does not depend directly on the mass of the structure itself, but mainly depends on the equivalent radius R according to the formula Eq. 1:

$$T_e = 2\pi \sqrt{\frac{1}{g \cdot \left(\frac{1}{R} + \frac{\mu}{d} \right)}} \qquad \text{Eq. 1}$$

where d is the displacement, g is the acceleration of gravity and μ is the coefficient of friction. Figure 2 shows the theoretical bi-linear hysteresis response of a CSS or DCCSS. The system is near rigid until the friction force $F_0 = \mu W$ is overcome, where W is the weight, then the force increase is proportional to displacement, with stiffness $K_r = W/R$ (named restoring stiffness).

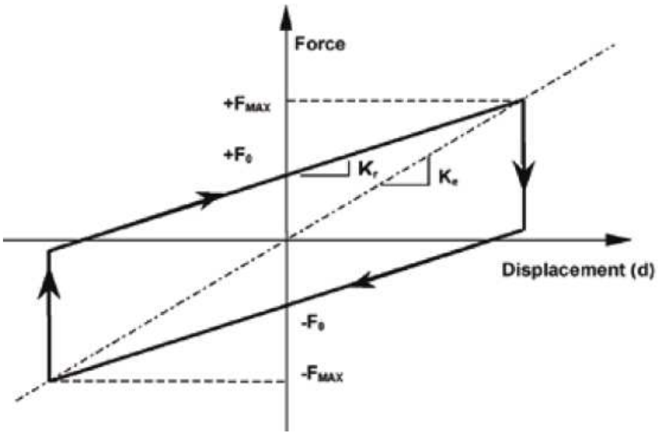

Figure 2: Theoretical force vs. displacement graph of CSS or DCCSS.

In order to determine the response of this seismic isolation system, the coefficient of friction is of crucial importance, since it's the main mechanism through which energy dissipation is achieved. A special sliding material coupled with stainless steel is used on the sliding surfaces to govern the friction. The selection of the sliding material is essential to give the curved surface sliders the necessary behaviour in terms of: i) load bearing capacity; ii) friction coefficient (energy dissipation); iii) stability of the hysteretic force-displacement curve with cycling; iv) durability; v) wear resistance (the latter mainly for bridges and viaducts, where cumulative non-seismic displacement is much larger than cumulative seismic displacement). The isolators object of this paper use an Ultra-High Molecular Weight Poly-Ethylene (UHMW-PE) as sliding material. The UHMW-PE is characterised by exceptional properties in terms of load bearing capacity, wear resistance, stability and durability.

For any sliding material the friction coefficient is known to be dependent on both velocity and pressure.

From available studies (e.g. on PolyTetraFluoroEthylene-PTFE) it is well known that the coefficient of friction increases as the sliding velocity increases, up to a certain velocity where friction remains constant or decreases gradually. The relationship between the coefficient of friction and sliding velocity, modelled by Constantinou et al. [7] and used in many commercial softwares [8], [9], is described by an exponential function Eq. **2**.

$$\mu = \mu_{fast} - (\mu_{fast} - \mu_{slow})e^{-\alpha|v|} \qquad \text{Eq. 2}$$

Where μ_{fast} and μ_{slow} are the sliding coefficients of friction at large and nearly zero sliding velocities, respectively, and α is a rate parameter that controls the transition from μ_{slow} to μ_{fast}.

As known from literature and confirmed by test results, the dependence on pressure (vertical load) is not negligible; in particular the friction coefficient decreases at the increase of the vertical load. An example of relationship between the friction coefficient and the pressure for thermoplastic materials is given in the European Standard on Anti-seismic devices [10], § 8.3.4.1.5.

In this study, the dependence of friction coefficient on the velocity and vertical load is investigated, using available experimental data from a number of characterisation tests performed on full-scale double concave curved surface sliders equipped with UHMW-PE sliding material.

3 EXPERIMENTAL CAMPAIGN

3.1 Testing campaign based on European Testing protocol

Today the European Standard EN 15129:2009 on anti-seismic devices [10] is regarded to be the most detailed standard concerning testing procedures and requirements of anti-seismic devices, taking into consideration important parameters, such as vertical load, velocity, signal shape etc., when dynamic testing is required.

In accordance with the European Standard EN15129 the performance characteristics that define the quantifiable characteristics of the curved surface sliders shall be determined by Type Tests. Since dynamic friction is the mechanism through which energy dissipation is achieved by the isolators, it is important to determine their response by performing a series of sliding isolation tests, carried out on full-scale complete devices. In particular, the type tests shall be carried out on two identical isolators.

Table 1 lists the sliding tests required by EN 15129 as Type Tests. In Table 1, N_{Sd} is the design vertical load (in quasi-permanent load combinations, usually calculated as the average of the quasi-permanent load values acting on all the isolators of the same type used in a given structure); $N_{Ed,max}$ and $N_{Ed,min}$ are respectively the maximum and minimum seismic vertical load, and $N_{Ed,max}$ usually coincides with the nominal vertical load capacity (under earthquake) of the isolator N_{Ed}; d_{bd} is the design seismic displacement; v_{Ed} is the maximum design velocity.

The displacement input waveform is sinusoidal of the type $d_{(t)} = d_{bd} \cdot \sin(2\pi \cdot f_0 \cdot t)$. The dynamic friction coefficient must be determined from the energy dissipation, when computed for 3 cycles, as follows in Eq. 3:

$$\mu_{dyn,3} = \frac{1}{3} \cdot \sum_{i=1}^{3} \frac{A_{h,i}}{4 \cdot N_s \cdot d_x} \qquad \text{Eq. 3}$$

where $A_{h,i}$ is the area enclosed within the hysteresis loop in the i-cycle; N_s is the value of vertical axial load under which the isolator was tested; d_x is the value of the peak horizontal displacement achieved during the test.

Table 1: Test Matrix to verify sliding isolation behaviour in Type Tests according to EN15129.

Type of Test	Test Run	Compression Load Ns [kN]	Displacement d_x [m]	Peak velocity v_0 [mm/s]	Number of complete cycles
Service	S	N_{Sd}	maximum non seismic movement	5	20
Benchmark	P1	N_{Sd}	$1.0 \cdot d_{bd}$	50	3
Dynamic 1	D1	N_{Sd}	$0.25 \cdot d_{bd}$	v_{Ed}	3
Dynamic 2	D2		$0.5 \cdot d_{bd}$	v_{Ed}	3
Dynamic 3	D3		$1.0 \cdot d_{bd}$	v_{Ed}	3
Integrity of overlay	O	N_{Sd}	$1.0 \cdot d_{bd}$	v_{Ed}	3
Seismic	E1/E2	$N_{Ed,max}$ and $N_{Ed,min}$	1.0 d_{bd}	v_{Ed}	3
Bi-directional	B	N_{Sd}	$1.0 \cdot d_{bd}$	v_{Ed}	3
Property verification	P2	N_{Sd}	$1.0 \cdot d_{bd}$	v_{Ed}	3
Ageing	P3	N_{Sd}	$1.0 \cdot d_{bd}$	50	3

According to EN15129, the experimental value of the restoring stiffness K_r should also be obtained from the average between the loading and unloading stiffness, calculated from the best-fit straight line determined by the least square interpolation of the response between ±95% of the peak displacement.

For this research campaign, the experimental data of type tests on eighteen (18) different typologies (thirty-six (36) isolators) were collected in order to investigate their dynamic behaviour in terms of dynamic frictional coefficient (μ_{dyn}) and restoring stiffness (K_r) at different vertical loading conditions. They are all equipped with UHMW-PE sliding material named type M (medium-friction). All the devices were designed and constructed in FIP for different projects, over the last 5 years and were prototyped tested according to the European Standard EN15129:2009. From the type tests performed on each device (Table 1) only the results of three dynamic tests were used for the scope of this paper; i) Dynamic Test D3; ii) Seismic Tests E1 and iii) Seismic Tests E2. According to the Standard the devices were subjected in these tests to a sinusoidal input waveform at maximum design displacement (d_{bd}) and maximum design velocity (v_{Ed}), tested at 3 different values of vertical load, namely non-seismic design load N_{Sd} (D3), Maximum Seismic Load $N_{Ed,max}$ (E1) and Minimum Seismic Load $N_{Ed,min}$ (E2). I.e., the only test parameter who varies in these 3 tests is the vertical load.

The maximum design vertical load of all 18 typologies ranges from 1670 kN to 17500 kN, with design seismic displacements ranging from 110 mm to 450 mm, and the maximum test velocities range from 250 mm/s to 660 mm/s. The radius of curvature varies from 3000 to 6000 mm. For comparison purposes, in the results discussion the vertical load is presented as the ratio of the vertical load N_{Sd} acting on the isolator to the maximum vertical load $N_{Ed,max}$, for simplicity named N_{Ed}.

The isolators were tested in four different testing laboratory facilities, featured with high performance equipment to perform dynamic tests on large full-scale isolators. Here below a short summary of the equipment of each laboratory:

a) ***FIP Test Laboratories (Padova, Italy):*** Tests were performed on the Biaxial Dynamic Test Facility. It is a two-degree-of-freedom system designed to accommodate all the types of isolation devices in full-scale, capable to apply high loads at high velocities and frequencies. The performance characteristics are: static maximum vertical load of 30000 kN and 20000 kN dynamically; horizontal actuator capacity of 3000 kN; ±500 mm total horizontal stroke and ±1570 mm/s maximum velocity (Figure 3) [11].

b) ***SIS Lab, University of Basilicata (Potenza, Italy):*** The Seismic Device Testing apparatus was used; it is characterized by maximum vertical load of 8000 kN, maximum horizontal load of ±1000 kN and maximum stroke ±500 mm (Figure 4) [12].

c) ***TREES Lab of Eucentre (Pavia, Italy):*** The Bi-axial Bearing Tester Machine was used for the testing of the isolators. It is characterized by a vertical load up to 40000 kN, horizontal forces up to 2000 kN, ±600 mm horizontal displacements, longitudinal peak velocity 2200 mm/s (Figure 5).

d) ***Caltrans SRMD Test Facility at the University of California San Diego, (USA):*** The Caltrans Seismic Response Modification Device Test System is a 6-DOF system with the following technical characteristics: vertical force 53400 kN and vertical moment 8136 kNm, longitudinal force 8900 kN and lateral force 4450 kN, longitudinal displacement ±1.22 m and lateral displacement 0.61 m, longitudinal velocity ±1.778 mm/s and lateral velocity ±762 mm/s (Figure 6). [13]

Figure 3: FIP Biaxial Dynamic Test Facility (left) and a DCCSS under test in it (right).

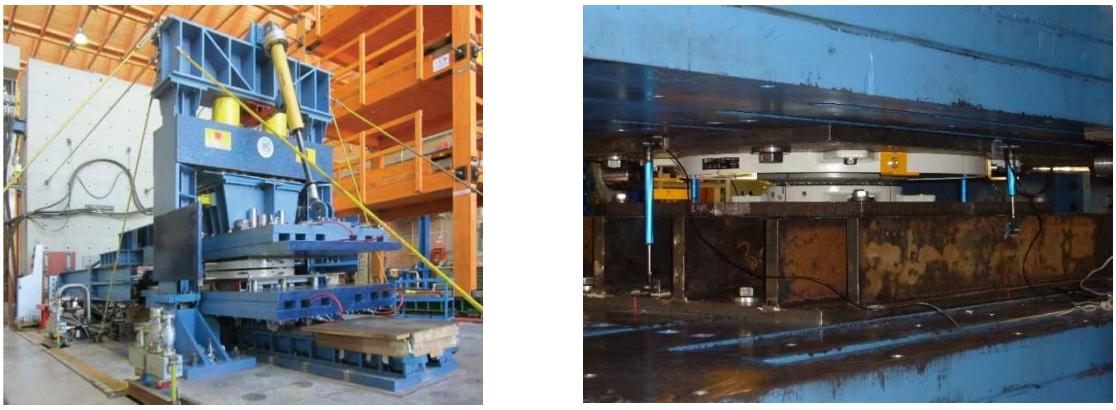

Figure 4: SIS Lab Dynamic Testing Facility (left) and a CSS under test in it (right).

Figure 5: TREES Lab of Eucentre Bi-axial Bearing Tester Machine (left)
and a DCCSS under test in it (right).

Figure 6: Caltrans SRMD Test Facility (right) and a DCCSS under test in this machine (right).

3.2 Sliding velocity and vertical load test campaign

An additional experimental campaign was carried out at the biaxial dynamic test facility in FIP on three double concave curved surface sliders of the same typology. The devices were subjected to a series of dynamic tests in order to study the dependence of friction coefficient on both vertical load and sliding velocity. They were subjected to sinusoidal input waveform with 90 mm amplitude at eleven (11) different peak velocities ranging from 5 mm/s up to 500 mm/s. Each unit was tested at different vertical loading conditions, namely N_{Sd} / N_{Ed} = 0.5, 0.75 and 1.0.

4 TEST RESULTS AND DISCUSSION

4.1 Vertical load dependence

Considering the typical load working conditions between 0.25 to 1.0 N_{Sd}/N_{Ed}, the experimental test results of the 36 isolators demonstrated the expected dependence of the coefficient of friction on vertical load. In Figure 7 the dynamic friction coefficient results as function of the applied vertical load, are reported. The vertical load is presented as the ratio of the design vertical load N_{Sd} (applied during the test) to the maximum seismic vertical load N_{Ed} (i.e. the capacity of each isolator).

As expected, the friction coefficient decreases at the increase of vertical load, ranging from an average of 10.0% for N_{Sd}/N_{Ed} in the range of 0.25÷0.5, to 7.7% for N_{Sd}/N_{Ed} in the range of 0.5÷0.75 to 5.5 % for N_{Sd}/N_{Ed} in the range of 0.75÷1.0.

The dynamic friction coefficient values presented in Figure 7 are corresponding to μ_{fast} as defined in Chapter 2, since they are measured in dynamic tests at maximum velocity. However, it is worth noting that such test velocities are different for each of the 18 typologies of isolators, ranging between 250 mm/s up to 620 mm/s.

These experimental data were interpolated with the law given in Eq. 4:

$$\mu_{max} = 5.7 \left(\frac{N_{Sd}}{N_{Ed}}\right)^{-0.588} \qquad \text{Eq. 4}$$

Although the small population of the devices and the lack of tests at certain values of the ratio N_{Sd}/N_{Ed}, this new experimental interpolation law is very similar to the existing experimental law derived from previous test campaigns carried out by FIP Industriale (Eq. 4) and used up to now for design of isolated structures [14]. Equation 5 is shown in Figure 7, together with the experimental results. The negligible error of about 5% between the old and the new law confirms the validity of the results of the previous testing campaigns and the stability of the production of the M (Medium friction) type of UHMW-PE sliding material used.

$$\mu_{max} = 5.5 \left(\frac{N_{Sd}}{N_{Ed}}\right)^{-0.563} \qquad \text{Eq. 5}$$

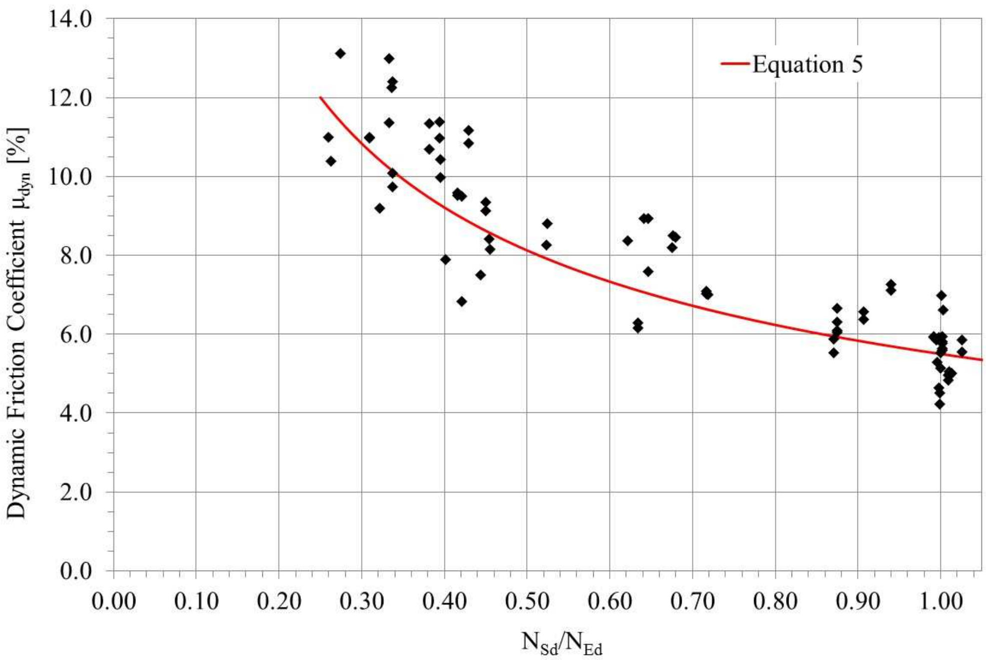

Figure 7: Experimental dynamic friction coefficient variation with the vertical load.

Figure 8 and Figure 9 provide the experimental force-displacement graphs obtained for two different isolators during the dynamic test D3 and Seismic test E1, i.e. at different vertical load and the same velocity and displacement. These two isolators are not comparable between them. The isolator with identification mark FIP-D M 1150/900(4500) (Figure 8) is characterised by maximum vertical load N_{Ed} of 3100 kN, 450 mm maximum displacement, 664 mm/s maximum test velocity and 4500 mm effective radius of curvature. The isolator with mark FIP-D M 1450/470(3100) (Figure 9) is designed for maximum vertical load N_{Ed} of 5600 kN, maximum displacement 235 mm, maximum velocity 269 mm/s and has 3100 mm effective radius of curvature. Both Figure 8 and Figure 9 demonstrate the vertical load dependence of both the dynamic friction coefficient and the restoring stiffness. The friction coefficient calculated in the first case (Figure 8) at N_{Sd} was 7.00% and was reduced to 5.87% at N_{Ed}, with 6% and 7% error, respectively, compared to the theoretical friction coefficient calculated with equation Eq. 5. The restoring stiffness was increased from 0.481 kN/mm for vertical load N_{Sd} = 2210 kN to 0.725 kN/mm for N_{Ed} =3100 kN, with a maximum error of 5% compared to the theoretical restoring stiffness. The second typology (Figure 9) exhibits 9.97% friction coefficient at N_{Sd} equal to 2160 kN and 5.56% at N_{Ed} equal to 5600 kN with the negligible error of 6% for test D3 and 0.5% for E1 when compared with the theoretical friction coefficient calculated with Equation (Eq. **5**). The experimental restoring stiffness in this case was calculated as 0.664 kN/mm for N_{Sd} equal to 2100 kN, increasing to 1.859 kN/mm for N_{Ed} equal to 5600 kN obtaining a maximum error of -5% compared to the theoretical values.

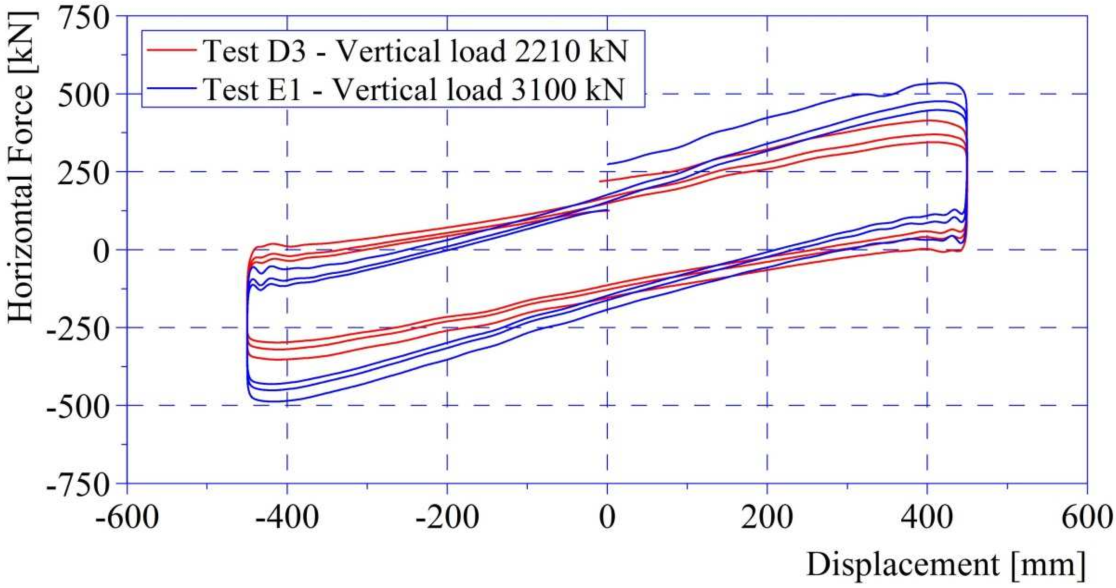

Figure 8: Experimental Force vs. displacement graph of the double concave curved surface slider FIP-D M 1150/900(4500) tested at two different loading conditions

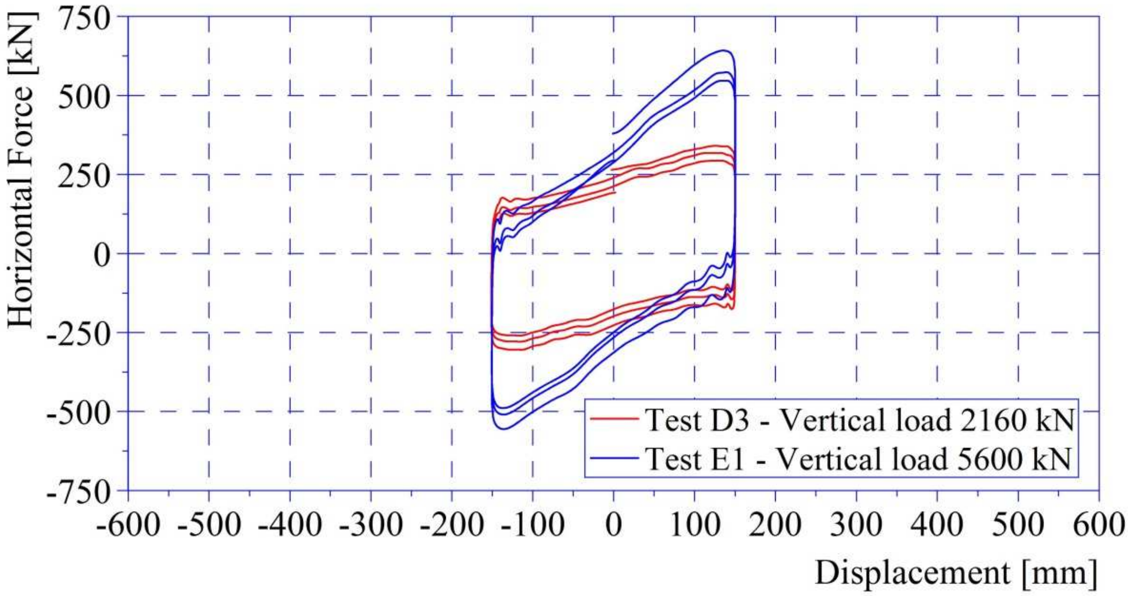

Figure 9: Experimental Force vs. displacement graph of a double concave curved surface slider FIP-D M 1450/470(3100) tested at two different loading conditions.

Figure 10 and Figure 11 provide the experimental hysteresis loops of the same devices of Figures 8 and 9, during the Benchmark test (Test P1, Table 1), that according to EN 15129:2009 is carried out as Factory Production Control Test as well.

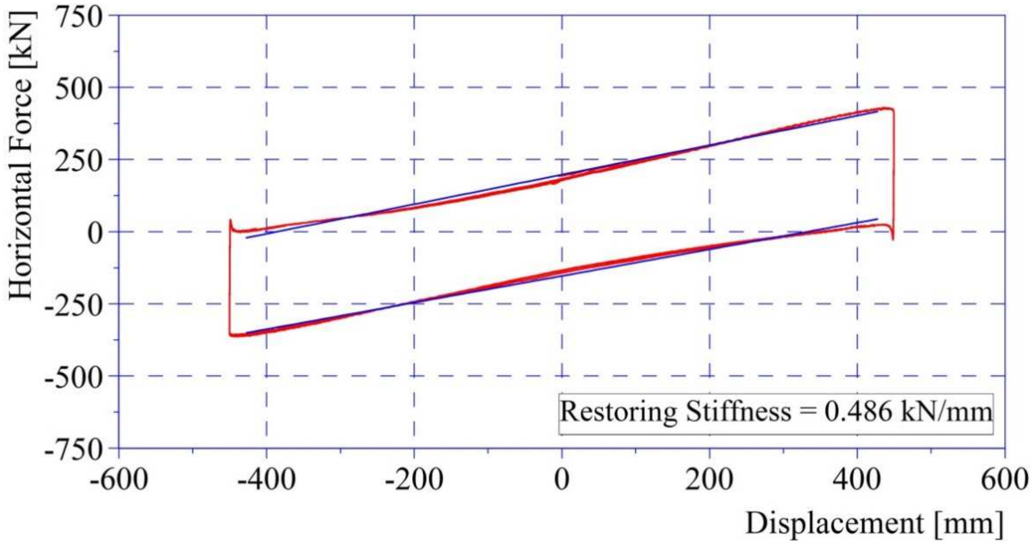

Figure 10: Benchmark Test – experimental force vs. displacement graph on double concave curved surface slider FIP-D M 1150/900(4500)

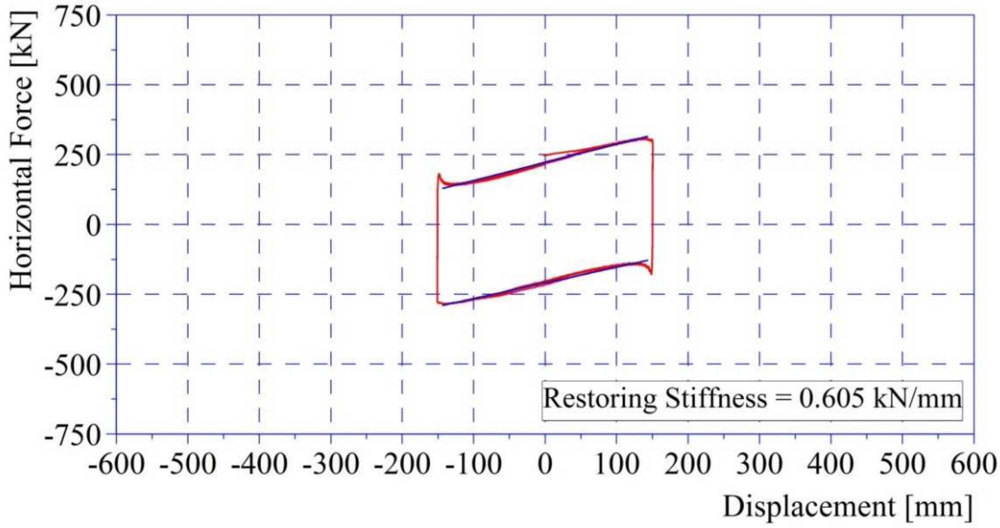

Figure 11: Benchmark Test – experimental force vs. displacement graph on double concave curved surface slider FIP-D M 1450/470(3100).

At this point it should be mentioned that, since all dynamic tests require a large amount of hydraulic power supply in order to reach the high velocities at high frequencies, all tests are performed imposing an initial and a final sinusoidal cycle of smaller amplitude, controlling in this way the initial acceleration which otherwise is very high. During the elaboration of the experimental data this part is excluded in order to calculate the actual energy dissipation of the device (Figure 8, Figure 9, Figure 10 and Figure 11 hysteresis loops).

4.2 Velocity dependence

In order to study the dependence on sliding velocity of the friction coefficient of the double concave curved surface sliders equipped with UHMW-PE sliding material named type M (medium-friction), three devices of the same typology (identified by mark FIP-D M 890/400(2500)) were subjected to a series of dynamic tests at their maximum design displacement at eleven (11) different peak velocities ranging from 5 mm/s up to 500 mm/s. Since the dependence on vertical load is already known, each of the 3 devices was subjected during the tests to a different vertical load, namely N_{Sd}/N_{Ed} equal to 0.5, 0.75 and 1.0, in order to check how different vertical loads affect the dependency on velocity. Figure 12 presents the experimental variation of the dynamic friction coefficient with the velocity. The friction coefficient measured in each test on a device is given as the ratio of the friction coefficient at each test velocity to the friction coefficient obtained from the Benchmark test (at 50 mm/s) on the same device.

The velocity and vertical load influence is evident. It is clear from Figure 12 that at lower velocities (<200 mm/s) the dynamic friction coefficient dependence is greater in all three loading conditions, whereas at higher velocities (>200 mm/s) the friction coefficient exhibits less variation. It is evident, furthermore, that as the vertical load increases the influence of the velocity becomes less important. The Coefficient of Variation (CoV) for slow velocities (up to 200 mm/s) was 16%, 14% and 12% for N_{Sd}/N_{Ed} equal to 0.5, 0.75 and 1.0 respectively. Instead the CoV for faster velocities (>200 mm/s) decreases at 4% for N_{Sd}/N_{Ed} equal to 0.5 and 2% for N_{Sd}/N_{Ed} equal to 0.75 and 1.0.

As it has already been said, the restoring stiffness depends solely on vertical load applied, thus no dependence on velocity is observed (Figure 13). All values are within the ±15% of the design value, as requested by the European Standard EN15129.

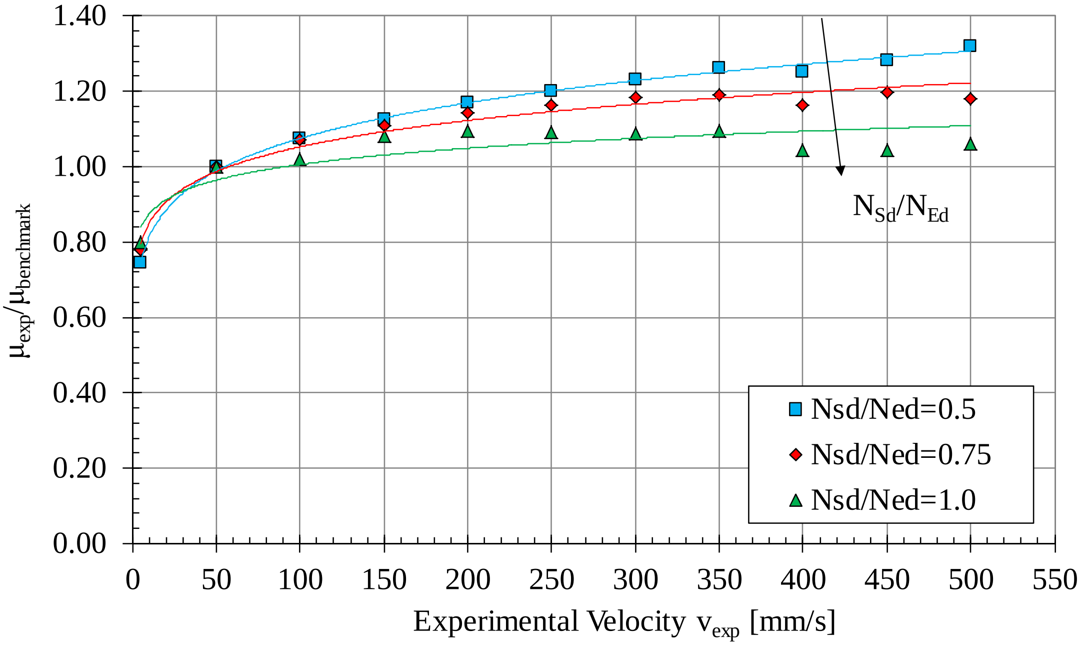

Figure 12: Normalized dynamic friction coefficient vs. test velocity

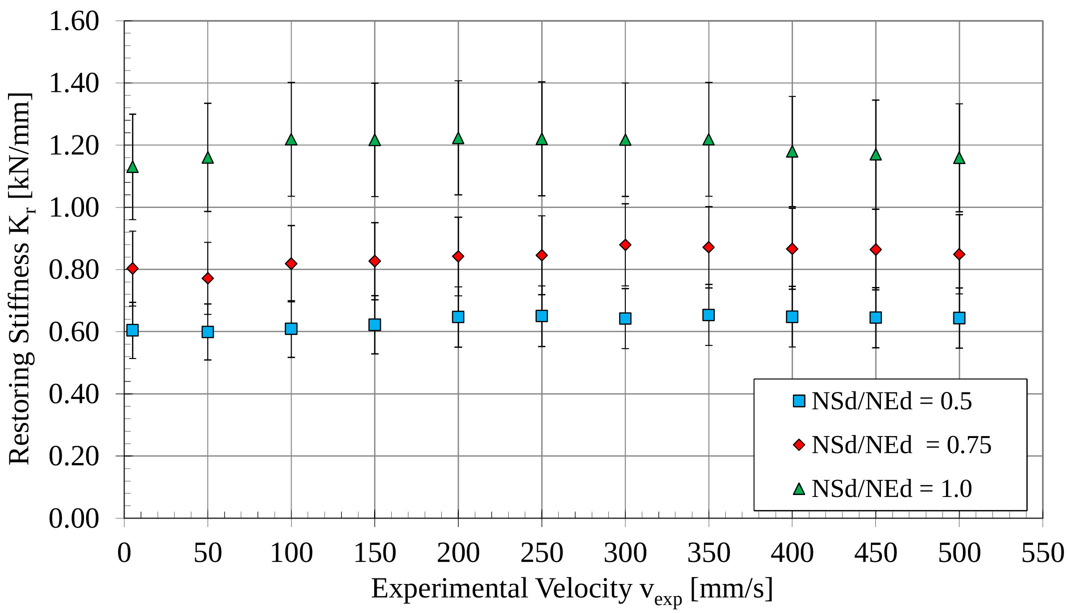

Figure 13: Restoring stiffness vs. test velocity

4 EXAMPLES OF APPLICATION

Nowadays seismic isolation with curved surface sliders is frequently used worldwide for bridges and viaducts, for strategic buildings such as hospitals and in some countries for private buildings as well. This chapter presents some examples of seismic isolation with the use of curved surface sliders, equipped with UHMW-PE sliding material, designed and produced by FIP.

In Italy, the application of Curved Surface Sliders (CSS), and in particular of Double Concave CSS (DCCSS), started in 2009, immediately after the 6th of April, L'Aquila earthquake. The biggest application is that of the C.A.S.E. Project, that is residential buildings built in L'Aquila by the Civil Defence to host the people left homeless by the earthquake. FIP supplied almost 2500 DCCSS. In this project the same isolation system was used for different types of building structures, e.g. steel, wood, concrete. According to the technical specifications required, the DCCSS had a curvature radius of 4000 mm, maximum displacement of ±260 mm, maximum vertical load of 3000 kN with equivalent viscous damping higher than 20%. The isolators were equipped with UHMW-PE type M. The isolation units were submitted to both type tests and factory production control tests. The tests were performed at the EUCENTRE Laboratory of Pavia in Italy and further testing were carried out at the Seismic Response Modification Device (SRMD) at the University of California at San Diego, USA [1]. Figure 14 shows the typical configurations of installation, with steel columns below the isolators and a reinforced concrete slab above the isolators.

After L'Aquila earthquake, seismic isolation has been used in Italy much more than before, even in residential buildings, both new and existing, and in many cases DCCSS were used. For example, many buildings damaged by the earthquake in L'Aquila were retrofitted using seismic isolation [4].

Figure 14: C.A.S.E. Project, L'Aquila, Italy - Isolation unit being installed (left), basement with installed isolation units (right).

Between 2013 and 2018, FIP installed more than 2000 double concave curved surface sliders on five hospitals in Turkey i.e., the Van Medical Campus (512 units), Kahramanmaras Elbistan Hospital (455 units), Manisa Merkez Efendi Hospital (505 units), Tokat Erbaa Hospital (309 units) and Mugla Bodrum Hospital (245 units). The isolators are characterised by radius of curvature ranging from 3100 mm to 6000 mm, maximum displacement ranging from ±300 mm up to ±500 mm and vertical load from 1000 kN up to 22500 kN. In all cases, according to the European Standards and the clients specifications, type tests and factory production control tests were performed in the foresaid laboratories (UCSD-SRMD Laboratory in California, USA, SISLab, Eurocentre and FIP Laboratories in Italy). Photos in Figure 15 and Figure 16 show the installation of the isolators in some of the above mentioned hospitals in Turkey.

Figure 15: Van Medical Campus, Turkey - Isolation unit installed on top of a column (left), aerial view of part of the hospital during installation of isolators (right).

Figure 16: DCCSS as installed in Kahramanmaras Elbistan Hospital (left), and Mugla Bodrum Hospital (right), both in Turkey.

Similarly to many other countries, the use of pendulum isolators (DCCSS) in Chile is more recent than that of elastomeric isolators. In the last years, since 2011, three buildings have been seismically isolated through pendulum isolators, for example two commercial/office buildings [6]. These two buildings are both located in Santiago, thus the seismicity is similar, with PGA about 0.4g. The equivalent radius of curvature of the isolator is 3.1 m for the Kennedy building, and 3.7 m for the Nueva La Dehesa building. The design displacement is ranging from 250 mm to 350 mm. The building Nueva La Dehesa is an office building of more than 25.000 m^2, with some commercial activities in the first two floors. The isolators are located just below the ground level (Figure 17). The project has two similar and opposite buildings, one of them with seismic isolation, and the other one with conventional design. The buildings were already subjected to several seismic events, including the strong earthquake occurred offshore the region of Coquimbo on September 16th, 2015. During this event, the building without isolation system reported damage in secondary elements, especially in clearing one of its elevators, not allowing the offices to work properly. On the other hand, the isolated building did not report any damage; the activation of the seismic isolation system was appreciated, being able to visually see a maximum displacement of about 1 cm.

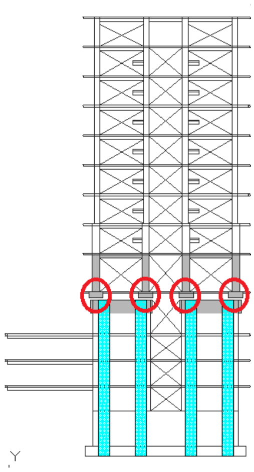

Figure 17: Elevation of Nueva La Dehesa Building, Santiago, Chile.

A very recent building application of double concave curved surface sliders is the extension of the Mall of Cyprus in Nicosia, presently under construction (Figure 18). In the new part of the Mall (approximately 6.000 m^2), six types of double concave curved surface sliders (total 137 units) with UHMW-PE type M sliding material were installed. The isolators are characterised by vertical load capacity ranging from 1280 kN to 5500 kN, 3100 mm radius of curvature, displacement capacity ±250 mm. According to the European Standards EN15129:2009, type tests and factory production control tests were performed at the FIP Laboratory. Furthermore, two isolators of different typologies were subjected to bi-directional testing i.e., Clover Leaf Test at the EUROLAB laboratory of Centre of Excellence for Research and Innovation on large dimensions Structures and Infrastructures (C.E.R.I.S.I.) of the University of Messina, Italy.

Figure 18: Extension of Mall of Cyprus under construction.

Another application of the double concave curved surface sliders is that in industrial tanks, both new and existing (seismic retrofit). From 2015 to 2017, FIP manufactured more than 1000 DCCSS for 7 different tanks, both in Turkey and in Iran, in areas characterized by high or very high seismicity. For example, 121 DCCSS of 3 types were installed to retrofit an ammonia tank in Samsun, Turkey. The supporting structure was already existing, thus one of the design criteria for the isolation system has been the reduction of base shear to a value lower than the elastic limit of the supporting structure [5]. The isolators are characterised by 4500 mm radius of curvature, ±450 mm displacement capacity and vertical load capacity ranging from 1840 kN to 3100 kN. In order to install the devices, the existing 121 columns were cut to create the proper room for the subsequent positioning of the isolator and the upper and lower steel anchor frames. After the completion of the installation of the devices, a new double wall refrigerated steel tank was placed over the existing isolated base. The isolators' plan layout is shown in Figure 19. Figure 20 shows the existing concrete slab and foundation and the installation of an isolator. The Type Tests carried out at the FIP Laboratory, in Italy, were performed according to the European Standard on Anti-seismic devices EN 15129:2009 [10] carrying out a series of quasi-static and dynamic tests. Additionally to the test program required by the standard, due to the criticality of the structure, the client requested a supplementary dynamic sliding isolation test in which the applied horizontal displacement equals the maximum displacement capacity of the device (d_{Ed}) equal to ±450 mm. The associated peak velocity (v_{Ed}) reached during the additional test was equal to 644 mm/s.

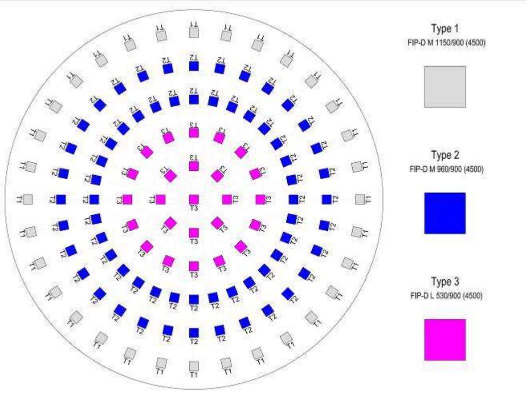

Figure 19: Ammonia storage tank in Samsun, Turkey: seismic isolators layout plan.

Figure 20: Ammonia storage tank in Samsun, Turkey, photos from the site: existing concrete slab and foundation before intervention (left), an isolator as installed in a column (right).

More than 1/3 of the total number of CSS or DCCSS manufactured by FIP (about 18000) are installed in bridges, in many different countries, from Italy to South Korea. A couple of examples in Italy are described in [2] and in [3], while Figure 21 shows a bridge in Almaty, Kazakhstan, the Saina Ryskulova Bridge. This is an example of the combined use of pendulum isolators and fluid viscous dampers, a combination that allows very high energy dissipation in earthquake conditions without transmission of too large friction forces in service conditions. In this bridge, DCCSS with two different friction coefficients were used, type M and type XL, the latter with about 1% friction coefficient.

Figure 21: Saina Ryskulova Bridge, Almaty, Kazakhstan.

5 CONCLUSIONS

The coefficient of friction is of crucial importance for the determination of the response of single and double concave curved surface sliders. Since friction is governed by the sliding material (always coupled with mirror-like finished stainless steel), its selection is essential to give the curved surface sliders the necessary behaviour. The Ultra-High Molecular Weight Poly-Ethylene (UHMW-PE) sliding material is characterised by exceptional properties, such as load bearing capacity, wear resistance, stability and durability. However, as for any sliding material, the friction coefficient depends on both sliding velocity and pressure (vertical load). It is well known that the coefficient of friction decreases as the pressure (vertical load) increases and that the sliding velocity can also influence the response of the device.

In this paper the dependence on vertical load of the friction coefficient has been investigated, using available experimental data from a number of prototype tests performed on 36 full-scale double concave curved surface sliders equipped with UHMW-PE sliding material, designed and manufactured by FIP Industriale, in Italy. All devices have been subjected to type tests according to the European Standard EN15129:2009; the tests were performed in four different testing laboratory facilities, three in Italy and one in USA, with high performance equipment able to perform both quasi-static and dynamic tests on full-scale isolators. The devices were of different curvature radius (up to 6000 mm), vertical loading conditions (up to 17500 kN), velocities (up to 660 mm/s) and seismic design displacements (up to 450 mm). Three dynamic tests were chosen from the European Standard testing protocol to study the behaviour of the 36 isolators. Considering the typical load working conditions (ratio between the testing load to the maximum load capacity under earthquake in the range between 0.25 to 1.0) the results demonstrated the dependence of dynamic friction coefficient (i.e. at fast velocities) on vertical load. The friction coefficient decreases at the increase of vertical load, ranging from an average of 10.0% for very small vertical loads to 5.5 % for high loads. The experimental data were interpolated providing an experimental exponential law for such dependency (friction coefficient vs. vertical load) that is very similar to that previously determined on the basis of other experimental data.

In order to study the dependence of friction coefficient on sliding velocity, a specific test campaign was performed in the laboratory of FIP in Italy. A series of dynamic tests were performed on 3 full-scale devices, at their maximum design displacement and at eleven (11) different peak velocities ranging from 5 mm/s up to 500 mm/s. Each device was subjected to a different vertical load, namely N_{Sd}/N_{Ed}=0.5,

N_{Sd}/N_{Ed}=0.75· and N_{Sd}/N_{Ed}=1.0. The results showed that friction coefficient is much more sensitive to vertical load rather than to velocity. However, by plotting the variation of friction coefficient with the velocity at the three different loading conditions, it was observed that at small velocities (of about <200 mm/s) the dependence is greater, whereas at higher velocities (>200 mm/s) the friction coefficient becomes more stable, especially at high vertical loads.

Further experimental tests are planned in order to develop a new model for the variability of friction coefficient with both pressure (vertical load) and sliding velocity.

During the last 10 years FIP has designed, manufactured and tested concave curved surface sliders for projects all over the world. Some examples of these projects are presented in the paper.

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