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EXPERIMENTAL ANALYSIS OF FRICTION MATERIALS FOR FREE from DAMAGE CONNECTIONS

G. Ferrante Cavallaro[(1)], A. Francavilla[(2)], M. Latour[(3)], V. Piluso[(4)], G. Rizzano[(5)]

[(1)] *PhD Student,Department of Civil Engineering, University of Salerno (Italy), gfcavallaro@unisa.it*
[(2)] *PhD Student,Department of Civil Engineering, University of Salerno (Italy), afrancavilla@unisa.it*
[(3)] *Post-doc,Department of Civil Engineering, University of Salerno (Italy), mlatour@unisa.it*
[(4)] *Full Professor,Department of Civil Engineering, University of Salerno (Italy), v.piluso@unisa.it*
[(5)] *Associate Professor,Department of Civil Engineering, University of Salerno (Italy), g.rizzano@unisa.it*

Abstract

The experimental analysis described in this paper has been performed within the activities of the FREEDAM project (FREE from DAMage steel connections), which is an RFCS project (Research Fund for Coal and Steel), granted by the European Community, devoted to the development of a new design strategy based on the employment of friction dampers in beam-to-column joints. In past, the application of dampers has been widely investigated within the development of supplemental energy dissipation strategies, with the aim to improve the energy dissipation capacity of the primary structure and to reduce the structural damage by concentrating the energy dissipation supply in fuses located in zones of the structure where high relative displacements are expected. Conversely, the strategy studied in the FREEDAM project is based on the application of damping devices, specifically friction dampers, under a new perspective. In fact, they are conceived as elements included in connections with the aim to completely substitute the traditional dissipative zones of MRFs, i.e. the beam ends. To this scope, beam-to-column joints are equipped with friction dampers constituted by steel plates and friction pads pre-loaded with high-strength bolts, that can be located either at the level of both flanges, or at the bottom flange level only, or on additional haunches which can be used to increase the lever arm of the damper.

In particular, the connection studied in the FREEDAM project is realized as a modification of the classical detail of a Double Split Tee Joint (DST) where, in substitution of the bottom Tee element, a symmetrical friction damper is introduced which is realized pre-loading friction pads located between the webs of a couple of angles used to fasten the beam to the column and the beam flange or the lower plate of a haunch, which is slotted in order to allow the sliding of the damper. With this connecting system, under bending actions, the joint is forced to rotate around a rotation center located at the base of the upper T-stub web and the energy dissipation supply is provided by the alternate slippage of the lower beam flange on friction pads. In this way, provided that the steel components of the connection are properly over-strengthened, the joint resistance and the rotation capacity can be easily governed by calibrating the preload applied to the frictional interfaces and realizing slotted holes whose length provides an adequate stroke for the dissipative device. The main feature of this connection is that, even under the occurrence of destructive seismic events, the only damage is due to the consumption of the friction pads, while all the steel elements are completely preserved obtaining, in this way, a connection able to withstand destructive seismic events without any damage to the steel parts, namely a FREE from DAMage connection. Clearly, in order to accurately control the design of such a connection typology, the knowledge of the value of the friction coefficient of the material employed to realize the friction pads is of paramount importance. Therefore, among all the possible materials, it is necessary to select those able to develop high values of the friction coefficient and a stable behavior under cyclic loading conditions.

In this paper, the main results of preliminary analyses devoted to select the best materials to be employed as friction pads in the FREEDAM connections are presented. To date, twelve tests on eight different materials combined with stainless steel plates have been realized. The tests performed, mainly devoted to evaluate the behavior of the friction interfaces in terms of static and kinetic friction coefficient and in terms of degradation, are inspired to the sliding test proposed by EN1090-2 adopting the loading protocol suggested by the EN12159 for the qualification of seismic devices. The initial value of the friction coefficient and its evolution during the tests, have been determined for the different materials by monitoring the values of the forces of the bolts used to apply the pre-load to the friction interface and the value of the sliding force. The obtained results are presented both in terms of force-displacement curves and in terms of friction coefficient, providing a comparison between the performances of the analyzed interfaces in terms of energy dissipation supply.

Keywords: friction connections, friction coefficient, sliding tests, dissipation, FREEDAM joints

1. Introduction

Modern seismic codes are based on the definition of performance levels, providing to design structures to remain elastic in case of ordinary seismic events (Serviceability Limit State) and to damage under the occurrence of destructive seismic events (Ultimate Limit State). In order to govern the failure mode of the structure promoting the development of a dissipative mechanism of global type, such a damage has to be controlled by selecting specific zones which have to be engaged in plastic range in order to absorb the inelastic demand required by the seismic action. According to EC8 [1], in case of steel Moment Resisting Frames (MRFs), the dissipative zones can be located either in beam ends or in connections, designing full-strength or partial strength joints. In the first case, connections and columns are designed to be over-resistant with respect to the maximum action that can be transferred from the plastic hinges located in the beam ends, accounting also for the overstrength deriving from random material variability [2,3] and strain-hardening of material [4,5]. Conversely, in the second case, in order to foster plasticization in the connecting elements, joints are designed to be partial strength and, therefore, only a part of the bending moment is transferred to the column which, also in this case, has to be designed following members' hierarchy criterion [1]. The former approach is more classical and it has been already validated in many past experimental and theoretical studies, demonstrating the ability of this design philosophy to provide structures with adequate performances under seismic loading conditions both due to the high dissipative capacity provided by the plastic zones and to the possibility to avoid the development of soft-storey mechanisms [5-8]. Conversely, the latter design approach has been introduced in EC8 only recently and, even though it has also already been subject of a number of theoretical and experimental studies [9-17], it deserves further investigations able to fill the knowledge gap that still remains on various topics, such as the monotonic and cyclic ductility of connections, the codification of design criteria for dissipative joints and the development of dissipative connections employing elements easy to replace after the occurrence of destructive seismic events [18-22]. Independently from the adoption in practical design of one or another design philosophy, both these approaches have the main drawback to accept the occurrence of high levels of damage in the plastic zones leading to the need for reparations in the earthquake aftermath in structural members or in connections. Such a damage, obviously, represents a significant burden from the economical point of view, and, this is the reason why, in past years, as an alternative, several researches have been focused on the development of systems able to reduce the structural damage. In particular, among the various possibilities, supplemental energy dissipation systems have been proposed and extensively studied since the 90s, providing a wide set of dissipative devices to be inserted in particular zones of the structure, where high relative displacements or velocity are expected under the action of severe ground motions. In this way, a part of the energy dissipation supply is entrusted to dissipative fuses specifically designed for the energy dissipation, while the damage to the main structure is limited, reducing the seismic inelastic demand. Currently, a number of dissipative devices based on this design concept has been proposed, providing systems based on the activation of simple dissipative mechanisms such as yielding of metals, dry friction and viscosity of fluids [23,24].

Starting from this brief background, in order to overcome the drawbacks related to the adoption of the classical design strategies, recently, researches devoted to the proposal of a new design strategy whose goal is the development of an approach able to provide connections with friction dampers designed to avoid structural damage both in case of frequent and rare seismic events have been carried out [25-32]. Such an approach is based on the application of dampers under a new perspective. In fact, while energy dampers have been typically applied in passive control strategies with the aim of protecting the primary structure by integrating the energy dissipation capacity with the inclusion of new elements in zones where high displacements or velocities occur, conversely, in the new design strategy, the adoption of friction dampers is conceived in such a way to substitute the traditional dissipative zones of MRFs, with the aim to protect from damage both the structural and the connecting elements. To this scope, beam-to-column joints are equipped with friction dampers constituted by steel plates and friction pads pre-loaded with high-strength bolts, that can be located either at the level of both flanges, or at the bottom flange level only, or on additional haunches which can be used to increase the lever arm of the damper [33]. This is the subject of the FREEDAM project, which is an RFCS project, granted by the European Community, devoted to the development of strategies for the application of such a kind of connections to steel structures.

In particular, the typical layout of the connection under investigation in the FREEDAM project, is realized starting from a modification of the classical detail of a Double Split Tee Joint (DST) where, in substitution of the bottom Tee element, is introduced a symmetrical friction damper realized pre-loading friction pads and the webs of a couple of angles used to fasten the beam to the column, on the beam flange or on an additional haunch, which is slotted in order to allow the sliding of the damper (Fig.1). With this connecting system, under bending actions, the joint is forced to rotate around the rotation center located at the base of the upper T-stub web and the energy dissipation supply is provided by the alternate slippage of the lower beam flange on friction pads. In this way, provided that the steel components of the connection are properly over-strengthened with respect to the maximum action transferred from the friction damper, even under the occurrence of destructive seismic events the only damage is due to the consumption of the friction pads, while all the steel elements are preserved obtaining a connection able to withstand destructive seismic events without any damage to the steel parts, namely a FREE from DAMage connection. From the design point of view, in such a kind of connections, the bending moment transferred from the beam to the column is easily governed by calibrating the slippage force of the friction damper located at the beam lower flange or on the additional haunch, which is the result of the product of the friction coefficient (arising between the friction pads and the steel composing the beam or the haunch), multiplied for number of friction interfaces (two in case of a symmetrical damper) and for the sum of the pre-tightening forces applied with the bolts used to fasten the web plates of the angles employed to connect the beam to the column. Therefore, in order to govern the resistance of the FREEDAM connections, it is necessary to control the pre-loading force applied with the bolts and to characterize accurately the value of the friction coefficient of the material employed to realize the friction interface. In particular, as already well known, the bolt pre-loading force can be controlled by applying one of the methods already suggested by EN1090-2 (i.e. combined, torque, DTI washers) which are conceived to guarantee the minimum 95% reliability on the tightening required by EN1990 [34]. Conversely, the value of the friction coefficient that a determined interface is able to develop is something that needs to be characterized experimentally and depends on a plurality of factors. In particular, as already demonstrated in past experimental works, the friction coefficient of an interface strongly depends on the materials employed to realize the friction interface and on the main tribological properties, such as the superficial finishing, micro and macro hardness, shear resistance of the materials and roughness.

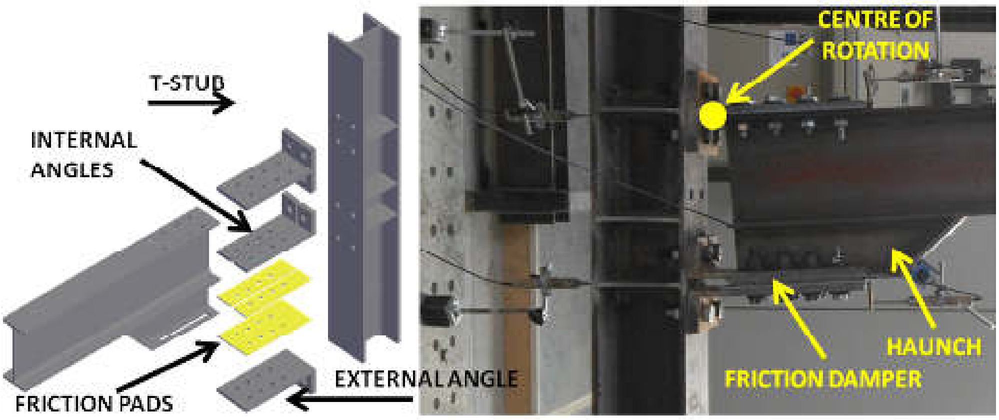


Fig. 1 –Typical layout of a FREEDAM connection

Within this framework, even though some works on the characterization of the frictional behavior of interfaces for seismic dampers are already available, it is clear that in order to develop the particular application under study in the FREEDAM project, it is necessary to perform experimental tests aimed at selecting among all the possible materials, those able to develop a behavior appropriate for the application in connections. The materials to be employed in the FREEDAM joint, clearly, have to be able to develop high values of the friction coefficient in order to reduce, as much as possible, the size of the employed friction dampers (in fact, the higher is the value of the friction coefficient and the lower is the number of bolts needed to carry a fixed value of the force) and to provide a stable response under cyclic loading conditions in order to guarantee a high energy dissipation capacity. In this paper, the main results of preliminary analyses devoted to select the best materials to be employed as friction pads in the FREEDAM connections are presented. To date, twelve tests on eight different materials combined with stainless steel plates have been realized. The performed tests are mainly devoted to evaluate the behavior of the friction interfaces in terms of static and kinetic friction coefficient and in terms of degradation. They are realized with a layout inspired to the sliding test proposed by EN1090-2 [35], while the loading protocol employed is that suggested by the EN12159 [36]for the qualification of seismic devices. The initial value of the friction coefficient and its evolution during the test have been determined for the different materials by monitoring the values of the forces of the bolts used to apply the pre-load the friction interface and the value of the sliding force. The obtained results are presented both in terms of force-displacement curves and in terms of friction coefficient, providing a comparison of the performance of all the analyzed interfaces with a focus also on the energy dissipation capacity.

2. Former tests on friction pads and selection of tested materials

To date, several studies have already been devoted to the analysis of friction materials for seismic devices and friction connections. Mainly, past studies have been focused on the analysis of friction materials especially for application to supplemental energy dissipation devices [37-40] but, more recently, similar studies have also been developed for application of friction dampers in connections or for the development of particular types of friction joints with finger plates for tubular steel towers. In particular, significant works dealing with the characterization of the behavior of friction interfaces have recently been performed within the activities of the HISTWIN project in [40-42] (where static friction connections for application in steel wind towers have been studied), and by the research group of the University of Auckland [27-30,43] that have already performed a number of cyclic tests both on elementary connections and joints equipped with asymmetric friction dampers, have been carried out. In addition, other works dealing with the characterization of the friction coefficient of interfaces have also already been developed in [32]. Clearly, all these works can be used as reference to provide a rational selection of materials to be tested for the application in FREEDAM connections.

In particular, from past studies, it is well known that in case of interfaces combining friction pads with a steel plate, high values of the friction coefficient can be achieved, provided that materials with a strong difference of the superficial hardness are coupled [43]. There are several possibilities to obtain this difference, but the materials mainly employed in technical literature or suggested by industries for realizing friction interfaces in combination with steel are normally ***metals, rubbers or carbide alloys***. Some of these categories of materials have already been investigated in combination with steel by several authors in past experimental activities such as high-strength tempered steels, brass or phenolic rubbers. Examples of experimental works already carried out are that performed in [43] on normal and abrasion resistant steels and the work performed in [32] on mild steel, brass, sprayed aluminum and different types of rubbers.

In particular, past experiences have evidenced that interfaces constituted by steel plates sliding on ***mild, abrasion resistant and high strength steel*** [43], can develop a high value of the friction coefficient (0.1-0.25 mild steel, 0.2 high strength steel, 0.4 abrasion resistant steel) but, they are normally characterized by a significant strain hardening behavior due to damage and increase of the ploughing component. Obviously, such a feature is not advantageous to friction dampers. In fact, a device characterized by a strain-hardening behaviour represents a strong limitation for the application because, if the friction devices are subjected to strain-hardening, then it is required that all the other elements of the connections and the columns have to be over-strengthened with respect to this increased values of the forces, leading to a strong oversizing of all the elements of the frame. In a similar way, friction shims made of ***abrasion resistant steel***, even though are able to develop a higher value of the friction coefficient (about 0.4) are still characterized by a significant strain-hardening, which makes this material not appropriate for the application for the same reasons previously mentioned. Conversely, ***high strength steels*** provide a more stable response, but a lower value of the friction coefficient (about 0.2) which, as in case of mild steel leads to a big size of the friction devices. In other past experimental works, the possibility to combine steel with brass, sprayed aluminium and different types of ***rubbers*** [32] has also been examined. From this analysis it has emerged that rubbers typically used for application in braking systems (which are mainly constituted by phenolic resins) provide a stable response but a low value of the friction coefficient (ranging from 0.15 to 0.25).

In addition, they are characterized by a low value of the tensile resistance which makes their applicability very limited. In fact, even though they are able to develop sliding forces appropriate for application in joints, they can easily undergo brittle failures in holed sections due to the tearing actions normally arising on the friction pad. Also ***brass*** has been the topic of several studies devoted to characterize its friction behaviour [37,38,32] or to test its application in friction devices. In particular, in the work performed by [38], it has been pointed out, by means of tests on simple splice connections, that the friction coefficient of brass is approximately equal to 0.3. In [32] brass has also been studied by means of tests on splice connections with eight bolts and, also in this case, it has been pointed out that the initial value of the friction coefficient of brass is very limited (about 0.1) even though it tends to increase with the increase of the ploughing arising on the interface under cyclic loading conditions.

In [39] and in [32] simple connections employing steel plates coated with thermally sprayed aluminium sliding on steel have been tested under cyclic loading conditions. These experimental analyses have pointed out that the tribological response of thermally sprayed aluminium is characterized by the development of high values of the friction coefficient (higher than 0.4 and up to 1 depending on the steel plate finishing) and by a stable response under cyclic loading conditions characterized by a high energy dissipation supply. In addition, beyond these features, these experimental works have also pointed out that, thermally sprayed aluminium and, in general, thermal spray coatings are characterized by a high potential for industrial application due to their low cost. Therefore, on the basis of the promising results already obtained [39] and in [32] and considering the low cost of the application of coatings on steel plates by means of thermal spray, materials that can be applied by means of thermal spray techniques have been selected for the experimental tests described in this paper.

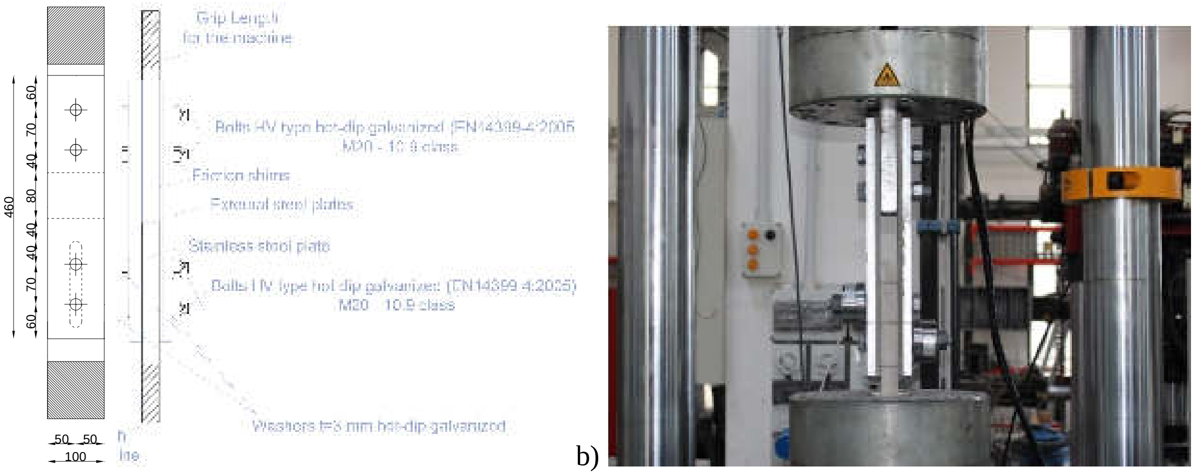
In particular, from the analysis of the available technical literature, eight materials that can be applied by means of thermal spray providing corrosion resistance (that is a fundamental requirement for the durability of the damper) and a value of the superficial hardness strongly different from that of steel (much higher or much lower) have been selected. The difference between the superficial hardness of plates in contact is a fundamental feature because as already hypothesized by Bowden and Tabor in [44] the friction coefficient (μ) of a metal interface is related to the ratio between the shear resistance of the weakest material (s_0) and to the superficial hardness of the softest material (σ_0) constituting the interface:

$$\mu = s_0/\sigma_0 \tag{1}$$

Therefore, in order to obtain a high value of the friction coefficient, a high value of the shear resistance of the weakest material and/or a very low value of the superficial hardness of the softest material are needed. Assuming that the internal surface of the friction damper proposed for the application to the FREEDAM connections is made of stainless steel AISI 304, which is characterized by a superficial hardness of about 130 HV, then the material to be coupled has to be characterized by a much lower or much higher value of the superficial hardness. In order to reach this scope, the materials' selection has been carried out by checking among the materials or alloys commercially available those characterized by very low o very high values of the superficial hardness. In the class of soft materials, five materials composed by non-ferrous pure metals or metal alloys with Vickers Hardness lower than 30 have been selected and labeled with the ID tags M1-M5. Conversely, in the class of "hard" materials, some carbide alloys produced as powder blends and electroless nickel friction shims produced by 3M Deutschland GmbH have been selected and labeled with labels from M6 to M8. These materials are characterized by superficial hardness higher than 550 HV. In particular, the friction shims produced by ***3M*** are ***Electroless Nickel shims*** realized with a particular blend including diamond powder, which is used to obtain a high value of the superficial hardness (600/900 HV). It is useful to note that, following the proposed approach it is expected that, when stainless steel is combined with harder materials, the consumption of the steel plate is promoted and, therefore, the friction coefficient obtained is mainly governed by the ratio between the shear resistance and superficial hardness of the steel plate. Conversely, when steel is combined with a softer material, the wearing of the interface is due essentially to the consumption of the friction shims and the friction coefficient mainly depends on the ratio between shear resistance and superficial hardness of the material employed to coat the friction shim.

3. Experimental layout

The typical specimen realized to evaluate the value of the friction coefficient of the analysed interfaces is composed by a system of steel plates assembled in order to test the uni-axial behaviour of friction interfaces resulting from the coupling of a stainless steel plate with friction shims coated with one of the eight materials previously described. The tested sub-assembly is inspired to the specimens' layout provided for slip tests by EN1090-2 [35]. In particular, it is constituted by a slotted steel plate realized in 1.4301 Stainless Steel [45] equivalent to AISI 304 steel, a steel plate with normal holes used to connect the specimen to the testing machine and external steel plates and friction shims pre-stressed with M20 class 10.9 HV bolts [46] (Figure 2a). The tested specimen aims to simulate the same conditions that are expected in the friction damper of FREEDAM beam-to-column connections. In particular, the stainless steel plate with slotted holes simulates the internal plate of an haunch that can be easily pre-fabricated and attached to the lower beam flange directly in the construction site in order to realize the friction damper (Fig.1), while the external steel plates aim to simulate the stems of the angles used to fasten the friction damper to the face of the column.



a) b)

Fig. 2 –a) Typical specimen; b) Specimen in the machine

In order to determine the value of the initial slippage force and its degradation, all the specimens have been tested under cyclic loading conditions following the loading protocol provided by EN15129 (2009) [36], which is the only code currently available devoted to the testing of displacement dependent dissipative devices. In particular, such a code requires to perform the tests under cyclic loading conditions aiming to reproduce the actual working conditions on the devices. To this scope, it suggests to apply to the damper increasing amplitude cycles at 25%, 50% and 100% of the maximum design displacement of the device. For the intermediate amplitudes it provides to perform at least 5 cycles and for the maximum amplitude it provides to perform at least 10 cycles. Therefore, in order to reach displacement amplitudes similar to those occurring in real applications, following the suggestions of EN 15129 (2009), the loading protocol was constituted by 5 cycles at the amplitude of 6.25 mm, 5 cycles at the amplitude of 12.5 mm and 40 cycle at the maximum amplitude of 25 mm. The maximum amplitude was defined by estimating the displacement demand arising at the friction damper level in real applications. Therefore, considering a reference value of the lever arm, i.e. the distance between the upper T-stub of the FREEDAM connection and the mid-center of the friction damper (Fig.1), equal to 600 mm and a maximum rotation of 40 mrad (greater than the minimum value required by EC8 equal to 35 mrad for DCH frames), the design displacement demand at the level of the damper has been calculated as equal to 0.04x600=24 mm, which has been rounded to 25 mm. The cycles were executed at increasing values of the speed that where defined in order to remain in a quasi-static range and according to the capabilities of the available equipment. The cycles' velocity varied from 1 mm/s for the first 10 cycles to 5 mm/s for the cycles at the maximum amplitude. In each test, both the upper and lower M20 high strength bolts have been tightened by means of a torque wrench, in order to reach the proof load equal to $0.7A_{bolt}f_{ub}$=0.7x245x1000=171500 N which has been controlled before starting the tests by means of appropriate donut load cells installed in the connection under the nuts of the bolts used to pre-stress the friction interface.

All the tests have been carried out employing a universal testing machine Schenck Hydropuls S56 (Figure 2b). Such a machine is constituted by a hydraulic piston with loading capacity equal to +/- 630 kN, maximum stroke equal to +/- 125 mm and a self-balanced steel frame used to counteract the axial load. Different sensors have been used before and during the test to control continuously the bolt force, the slippage load, the tightening torque and the displacement. The axial displacements of the device have been read directly from the transducer of the testing machine and, in the same way, the slippage force has been controlled directly exploiting the load cell of the machine. Before the test, the tightening torque has been applied through an hand torque wrench and monitored by means of a torque sensor Futek TAT430 with maximum capacity equal to 680 Nm. At the same time, the pre-tension applied to the bolts has been monitored before and during the test by means of donut load cells Futek LTH500 with maximum capacity of 222 kN. The donut load cell is a particular type of load cell that can be easily used to measure the clamping force applied to the bolts. Such a load cell has the typical structure of a shear beam cell, where the load is applied on a cylinder located in the middle of the load cell and it is transferred to an external cylinder through shear panels. Therefore, considering the structure of the load cell, aiming to preserve the distribution of pressure normally applied by the bolt to the friction interface, a thick and stiff washer with diameter equal to the external diameter of the load cell and a normal washer have been interposed in between the load cell and the external plates of the tested sub-assembly.

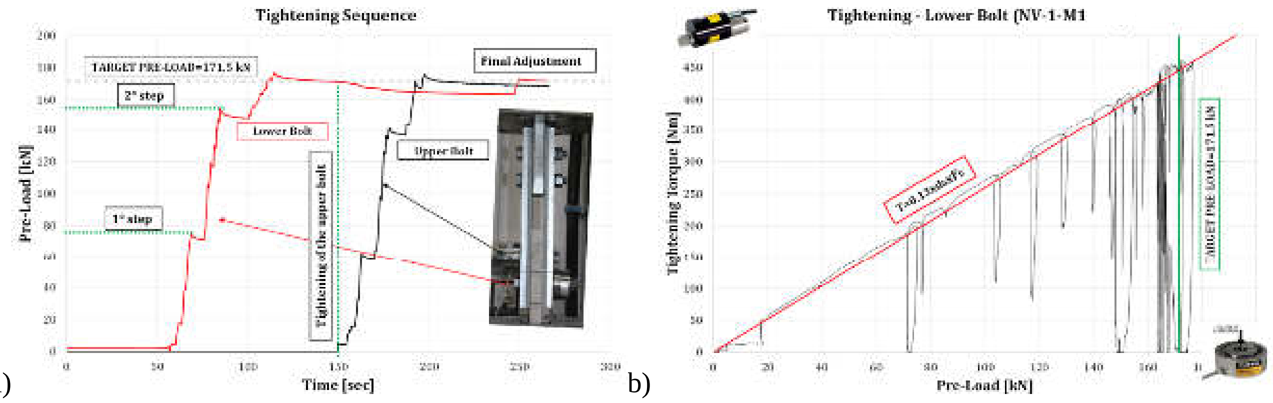
a) 

Fig. 3 –a) Tightening sequence; b) Typical Torque vs Pre-load diagram

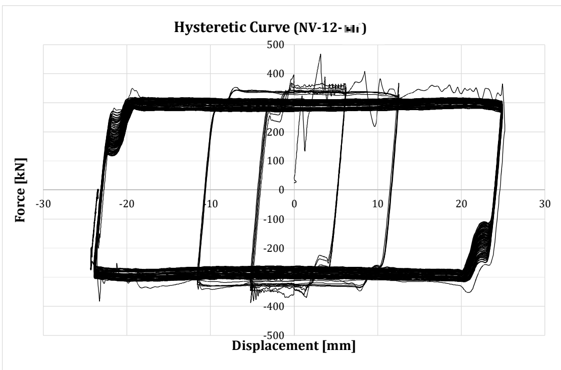
Before every test, the force has been applied to the bolts by means of a torque wrench, monitoring the tightening torque applied and the pre-loading force in the bolt. In particular, the adopted bolts had an average value of the k-factor equal to 0.13. Therefore, the value of the tightening torque applied to the bolts in each test was approximately equal to 0.13x171.5x20=446Nm. An example of the tightening sequence is reported in Fig. 3a where the force versus time diagram is given for the two bolts located in the lower part of the specimen. From this figure, it is possible to note that for each bolt the pre-load was applied in different steps before achieving the target value. At the end of each step, it is also possible to note that after releasing the torque wrench there was always an “instantaneous” loosening of the pre-load of about 5-10%. This is a well-known phenomenon due to the local crushing of microscopic spots of the steel parts in contact (embedment relaxation) that, in order to be exactly quantified, deserves deeper and more specific studies. Another effect that is possible to easily note from Fig. 3b is the group effect. In fact, the tightening of the second bolt, mutually influences the pre-loading force already applied in the other bolt.

4. Test results

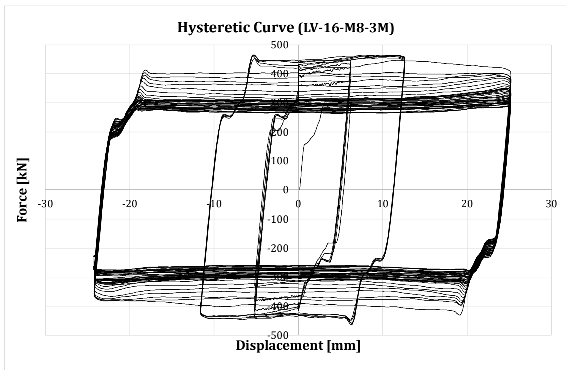
For each one of the eight materials previously mentioned two identical tests have been carried out. As aforesaid, in order to evaluate their performance under cyclic loading conditions, several parameters have been monitored during the test. In particular, in order to compare the friction coefficient of the various materials, the values of the slippage force and of the bolt forces read with the donut load cells have been exploited. Starting from the data acquired during the tests with the measuring devices employed, two different values of the friction coefficient have been characterized: an "effective" value and an "actual" value. In particular, the "effective" value ($\mu_{\text{effective}}$) of the friction coefficient has been calculated as the ratio between the slippage force and the sum of the nominal values of the pre-loading forces applied by the bolts (i.e. 4x171.5 kN). Such an effective value represents the value of the friction coefficient that can be used in seismic design and accounts as a whole both for the degradation of the friction coefficient due to the damage of the surfaces in contact and for the degradation due to the bolts' loosening. Conversely, the "actual" value of the friction coefficient (μ_{actual}) has been determined as the ratio between the slippage force and the sum of the values of the bolts' forces read from the load cells during the test. Such an actual value provides the real measure of the friction coefficient, whose degradation is due only to the damage of the surfaces in contact, while the effects coming from bolt loosening are directly measured by means of the donut load cells. In the following a synthesis of the obtained results is reported, describing the main experimental outcomes and providing a comparison between the different materials.

<u>Experimental behaviour of the "Hard" Materials (Carbide M6, Carbide M7, 3M friction shims (M8))</u>

A synthesis of the results of the tests on the interfaces coupling stainless steel with friction pads coated with the "hard" coatings previously described are delivered in Fig. 4, where the hysteretic curves of one of the two identical tests performed on each material are reported. It is worth noting that even though, in order to simplify the representation of the results, only the hysteretic curve of one of the two tests performed is reported, for all the three analysed materials, a very small scatter of the response for the two tests was observed, evidencing a very low random variability of the friction coefficient for these materials.



a)



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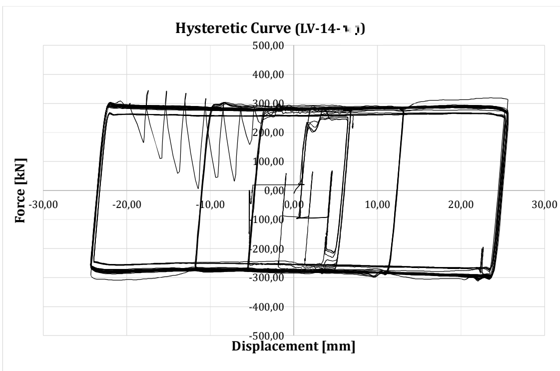
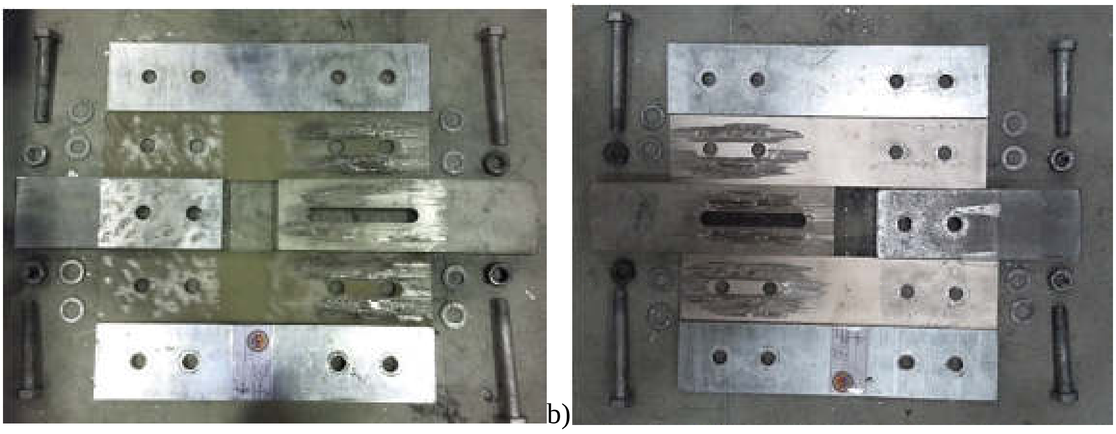


c)

Fig. 4 – Hysteretic behaviour of hard materials: a) Carbide M6; b) 3M friction shims; c) Carbide M7

In case of ***M6*** carbide coating, the cyclic response has been characterized by the development of an initial value of the slip force equal to about 350 kN, followed by a progressive degradation that, at the end of the test was of about the 20%. During the tests, a peculiar behaviour of this material has been observed. In fact, as it is possible to note from Fig.4a, the hysteretic curve was affected by an initial stick-slip phase with the development of a first unstable cycle characterized by jumps of the force and sudden releases of energy. Nevertheless, after this first cycle, that probably allows to break the initial interatomic attraction between the surfaces in contact (adhesion component of friction), the slippage occurred regularly leading to a very stable response up to the end of the test. In case of ***M7*** carbide coating, globally, a similar response was observed. The behaviour, in this case, was characterized by an initial slip force equal to about 250 kN, that after few cycles slightly increased, stabilizing at a value of about 300 kN. After reaching this value, all the cycles were characterized by the same slippage force obtaining, also in this case, a stable and dissipative behaviour. Even though the hysteretic behaviour reported in Fig.4c appears pretty similar to that observed for material ***M6***, in reality, in this case, in order to perform the test it was necessary to significantly reduce the velocity due to the development of a strong stick and slip behaviour, characterized by sudden releases of energy and vibrations. Therefore, to avoid any damage to the equipment, the testing velocity was reduced progressively up to a value of 0,01 mm/s in order to check if, with a lower value of the velocity, the stick and slip phenomenon disappears. In particular, the stick-slip is a well-known phenomenon of instability of the friction behaviour that provides the alternate and continuous sticking and slipping of the two surfaces in contact. According to the technical literature, this phenomenon is usually related to an high difference between the static and kinetic value of the friction coefficient which in some cases leads, after the first slippage, to a sudden jump of the velocity resulting in a deceleration until stopping. After stopping, to restart the movement, the interface needs again to reach a higher value of the force in order to overcome the static value of the friction coefficient, but then restarts, decelerates and, due to the same phenomenon, stops again. Usually, as observed in these tests, this behaviour results in a force-displacement response characterized by continuous jumps of the slippage force between the static and kinetic values. Even though the physical interpretation of the stick and slip behaviour is not easy and it is definitely out from the objectives of this work, it is obvious, from the response reported in Fig.4c, that it is a phenomenon not acceptable for the application of such materials in seismic damping devices. ***3M friction shims*** were characterized by a response that, as already observed in the past by the same authors with other materials such as brass or some types of phenolic rubbers [32], was characterized by two different phases of the response. A first phase where the interface provided a strain hardening behaviour characterized by an increase of the slippage resistance of about 60% and a second phase characterized by a reduction of the slippage force which, at the end of the degradation returned to the initial value. In addition, in this case no stick and slip response has been observed and all the cycles have been characterized by a stable value of the slippage force. The initial value of the slippage force has been of about 400 kN.



a) b)

Fig. 5 – Damage of the interfaces: a) M6; b) 3M friction shims;

After the tests, the specimens have been opened in order to evaluate the damage of the interfaces. In Figs. 5a,5b the damage state of the interface is represented for specimens employing M6 and 3M friction shims. As it is possible to observe from this figure, for these materials, due to the higher hardness of the coating layer with respect to stainless steel, the greatest part of the damage was concentrated on the stainless steel plate which at the end of the test had many scratches in the zone located under the bolt head. In Fig.6, as an example, the diagram of the bolt forces (monitored by means of the load cells) and of the actual friction coefficient represented versus the cumulative travel done by the damper are reported for the specimen with friction pads coated with M6 carbide. From such a figure it is possible to observe that both bolts, which are initially tightened in order to reach the proof load equal to 171.5 kN, after the first cycle of the loading history lose about the 7% of the initial pre-load and afterwards they uniformly loosen during the test reaching at the end a total loss of about the 20%. Clearly, this initial loss, that seems to occur just after the first sliding of the connection, should be properly accounted for in the design of the damper. From the comparison between Fig.4a and Figs.6 it is possible to note also that the degradation of the sliding force observed during the test is essentially due to the degradation of the bolts' forces. In fact, they both degrade of about the 20% while the "actual" friction coefficient remains constant. Even though, for the sake of simplicity, detailed graphs representing the behaviour of the bolts and the degradation of the friction coefficient for the other materials are not reported, analogous results have been obtained for all the other "hard" interfaces. Therefore, also for the other interfaces a correspondence between the bolts' loosening and degradation of the sliding force has been observed.

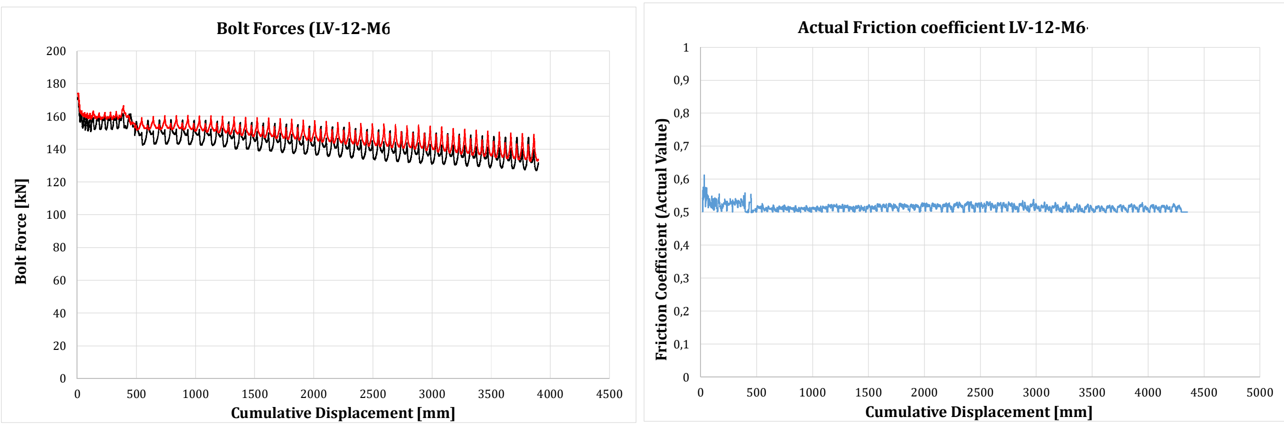


Fig. 6 – Typical diagrams of the bolt forces and „actual" friction coefficient vs cumulative travel: M6;

<u>Experimental behaviour of the "Soft" Materials (M1-M5)</u>

Similarly to what occurred in case of M7 carbide, also some of the soft materials exhibited a behaviour characterized by the stick-slip phenomenon. This is the case of three of the selected non-ferrous metal, namely ***M2, M3 and M5***, whose response was characterized by alternate stops and starts of the motion with strong and sudden releases of energy (Figs.7a-7b). Therefore, also in all these cases the tests have been stopped prematurely in order to prevent damage to the testing equipment. For these materials, as reported in Fig.7a,7b, the initial slippage force was equal to about 200 kN and was followed by an increase of the slippage resistance up to about 400 kN which corresponds to a value of the friction coefficient equal to about 0.58. After the first sliding, the hysteretic behaviour has been characterized by alternate and continuous jumps of the force from the static to the dynamic values. It is worth noting that, even though the cyclic behaviour of these interfaces is evidently not appropriate for seismic applications, from the results obtained in this experimental analysis it seems that these materials, due to the high value of the friction coefficient, could be still promising for application in friction connections designed for static loads.

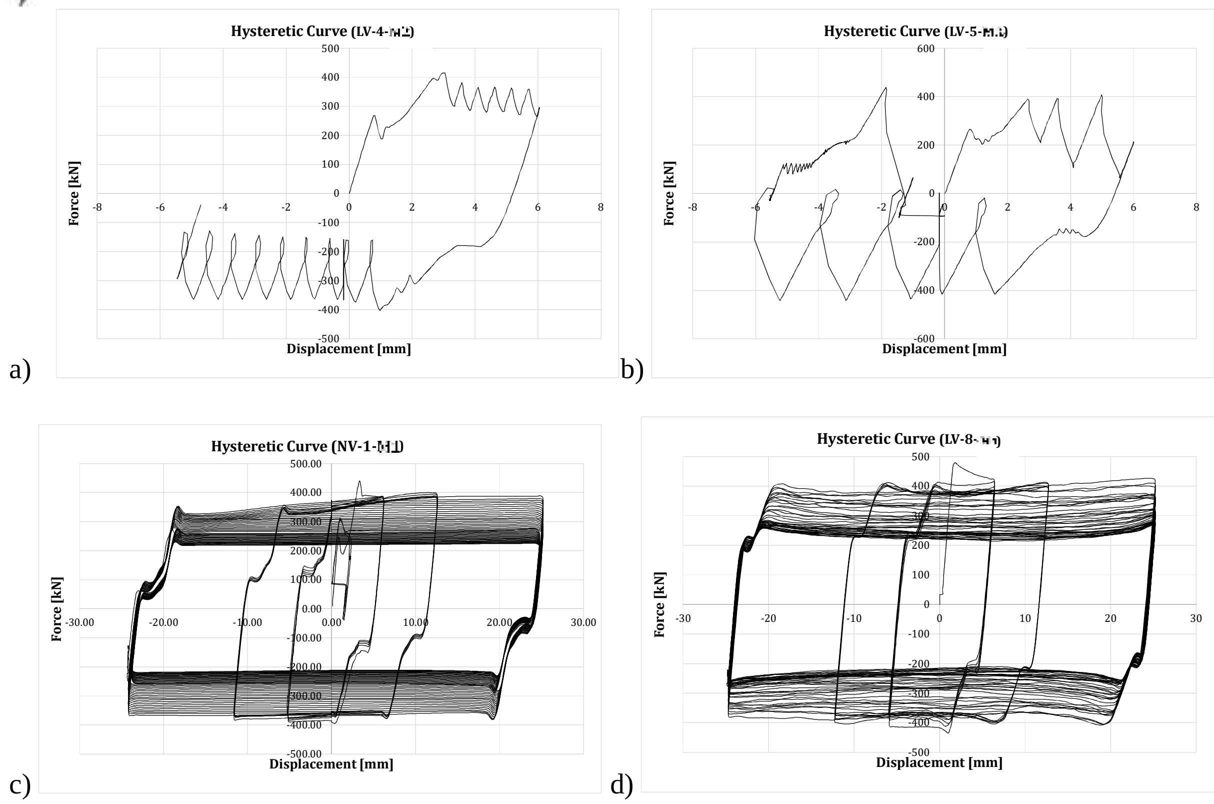
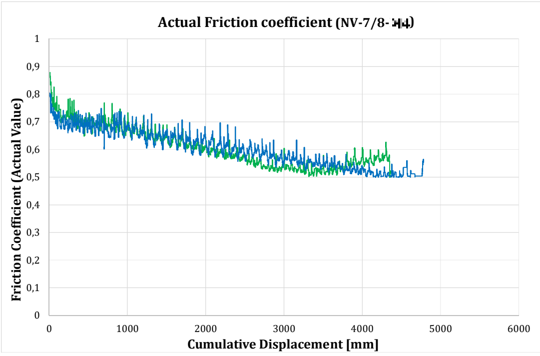


Fig. 7 – Hysteretic behaviour of soft materials: a) M2; b) M3; c) M1; d) M4

M1 and M4 metals have exhibited a very similar behaviour (Figs.7c-7d). In particular, their hysteretic response has been characterized by a value of the slippage force higher than the corresponding obtained with the “hard” materials but, on the other hand, they have also provided a more significant degradation due both to the bolt loosening and to the damage occurring in the friction pads. In addition, for both materials the behaviour exhibited in the two identical tests was significantly different showing a random variability of the behaviour of these materials. Such a variability was mainly due to the different behaviour provided by the bolts in the two tests. As an example, in Fig.8 with green and blue lines are represented the results expressed in terms of friction coefficient and bolt forces versus the cumulated travel, for the two tests executed on the specimens with M4 friction pads. From this graphs it is clear that, even though the actual value of the friction coefficient does not varies in the two tests, the bolts provide a significantly different behaviour leading, consequently, to a different response of the whole hysteretic response. In particular, in one of the two tests after the first sliding a sudden loss of pre-tension in the bolts of about the 15% was observed leading, as a consequence, to a proportional loss of the sliding force. Such a different response of the specimens can be probably due to the imperfections of the coating applied on the friction shims, which in case of soft coatings is completely manual and leads to a non-uniform spread of the coating metal. In case of material M1, the degradation of the initial slippage force at the end of the tests was the 45%, while in case of material M4 it was of about the 50%. Nevertheless, both materials provided very high values of the friction coefficient and, in particular, the initial friction coefficient of materials M1 and M4 were equal to about 0.55/0.65 and 0.7/0.9 respectively.

a)


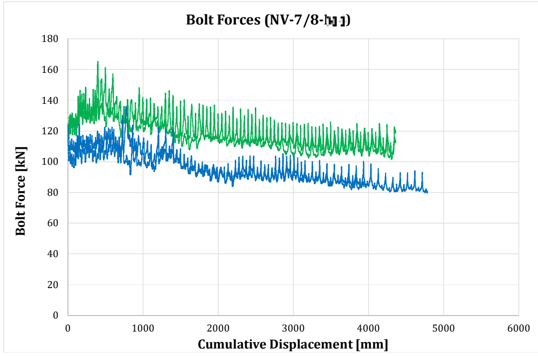
b)


Fig. 8 – a) Actual friction coefficient- M4; b) Bolt forces – M4

As in previous cases, also the specimens realized with soft materials were opened after the test, in order to evaluate the damage of the interfaces. As it is possible to note from Fig.9, as expected, in these cases the damage was mainly concentrated on the friction shims, while the stainless steel plates after the test were practically undamaged.

b)


d)


Fig. 9 – Damage of the interfaces: a) M1; b) M4

5. Discussion and conclusions

As reported before, the tests performed at low velocity have evidenced significantly different behaviours for the eight analysed interfaces. In particular, as previously described, some of the coating materials investigated (M2, M3, M5 and M7) provided a force-displacement response not appropriate for application to seismic devices, due to the development of stick-slip phenomena. Conversely, among all the materials investigated, some interfaces have emerged as promising alternatives for the application to FREEDAM beam-to-column connections. In particular, M1, M4, M6 coatings and the electroless nickel with diamond powder produced by 3M have provided high values of the initial friction coefficient and have shown an high energy dissipation capacity under cyclic loading conditions. A first quantitative comparison of their response has been carried out by plotting on the same diagram the effective and actual values of the friction coefficients obtained in the different tests (Fig.10). From such diagrams, it is possible to note that hard materials (M6 and 3M) have provided, in general, a lower value of the initial friction coefficient with respect to soft materials. The friction coefficient under cyclic loads, in case of M6 has been very stable, while in case of 3M friction shims it has been characterized by an initial increase of about 60% and, afterwards, by a continuous decrease up to the initial value of the friction coefficient. In addition, as reported in previous Sections, hard materials have provided a response practically coincident for the two analysed specimens, evidencing a low variability of their response which, from the practical point of view, may result in the possibility to predict with a higher accuracy the value of the friction coefficient to be used in design. The higher reliability of these interfaces, probably is due to the production process of these coatings, which as a difference with respect to soft materials is completely industrialized and allows to obtain an high level of control of the distribution of the coating layer applied to the friction shims. In fact, usually, in these applications it has been observed that the coating layer, due to the higher control of the application process, is normally uniformly distributed over the plate and with a very low variability of the coating thickness.

Conversely, soft materials (M1 and M4), even though, on one hand, have provided a better response in terms of initial value of the friction coefficient, on the other hand have also provided a higher variability of the response for the two tested specimens. In fact, in case of material M4, the value of the effective friction coefficient was significantly different for the two tests (0.90 and 0.70). In a similar way, also in case of material M1, the actual value of the friction coefficient was significantly different in the two tests. In fact in one test it was equal to 0.55, while in the other test it was equal to 0.65. Probably, the scatter obtained with the specimens employing soft coatings, can be linked to the production process that is typically performed by means of arc wire spray, which is a procedure completely manual that strongly relies on the individual capacity of the workman and on his experience. In fact, with arc wire spray, the coating is manually applied in different passes obtaining, at the end of the application process, a significant variability of the thickness of the coating layer. Such an inhomogeneous distribution of the coating thickness can be, normally, clearly observed also with the unaided eye.

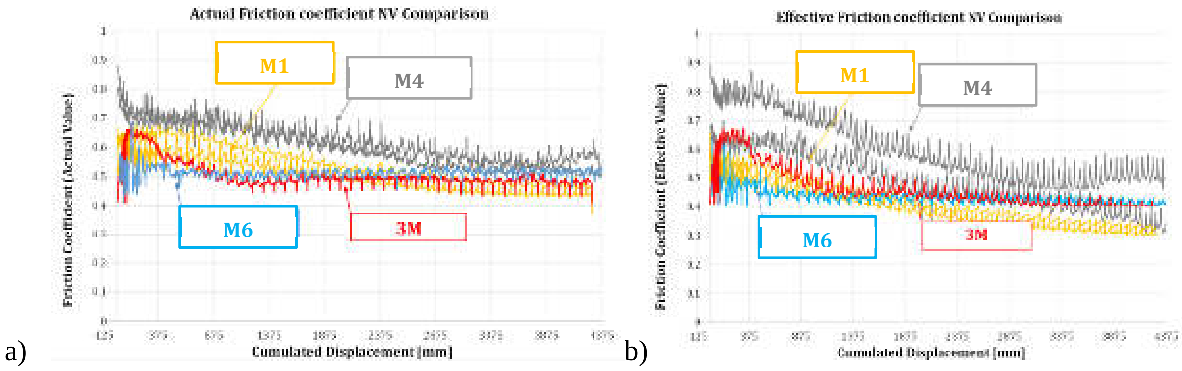


Fig. 10 – Comparisons

In conclusion, from the results reported in Fig.10 it seems that soft materials are able to provide an higher initial value of the friction coefficient with respect to hard materials. Conversely, hard materials are able to provide a low degradation under cyclic loading histories and a very low variability of the response. Only in case of friction shims coated with 3M electroless nickel, a strong increase of the friction coefficient initially occurs and, successively, a strong decrease of the friction coefficient can be observed. Probably, this high overstrength with respect to the initial slippage value is a disadvantage of this coating because, in seismic design, the adoption of this material would require a significant oversize of the non-dissipative parts of the frame and of the connections in order to allow the complete development of the dissipative mechanism in the FREEDAM connections. In terms of energy dissipation, all the four materials under consideration provided a significant capacity but, as it is possible to see from Fig.11 their energy dissipation capacity, due to the degradation of the friction coefficient under cyclic loading histories, is not constant and depends on the considered value of the cumulative displacement. In fact, from Fig.11 it easy to note that, up to a value of the cumulative displacement approximately equal to about 1700 mm, the materials which are able to dissipate the highest amount of energy are the soft materials. Conversely, for higher values of the cumulative displacement, hard materials are able to provide a higher value of the energy dissipation. Therefore, in order to understand what is the best material for application to the FREEDAM beam-to-column connections, from this point of view it is necessary to fix a target design value of the cumulative displacement that friction dampers realized with the proposed interfaces have to sustain under destructive seismic events. To this scope, a wide set of incremental dynamic analyses on case study buildings will be carried out in a subsequent phase of the work to be developed within the FREEDAM project in order to establish the maximum cumulative displacement expected under the action of real earthquakes.

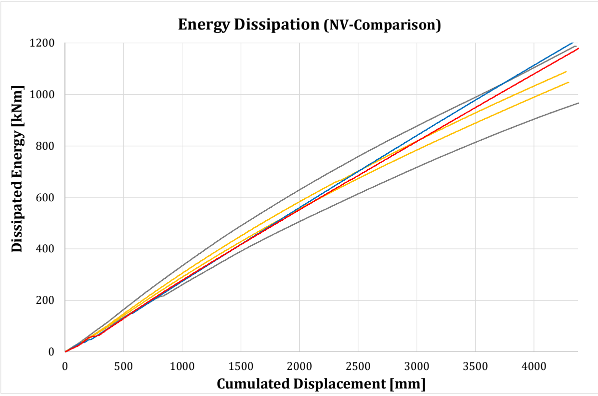


Fig. 11 – Energy dissipation capacity

7. Acknowledgements

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