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Experimental analysis of low-damage dissipative column base joints equipped with self-centring systems

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ABSTRACT
A FREE from DAMage friction connection is a connection where friction dampers are introduced by adding friction pads, sliding on slotted steel plates, pre-stressed with high strength bolts. Even though such a technology provides great advantages in terms of removal of damage to the structural elements, it has the main drawback to provide a limited re-centering capability. In fact, during a seismic loading history, FREEDAM joints rotate concentrating the dissipation in the friction interface but, due to their high stiffness, after the end of the ground motion, they remain in a deformed position, leaving also the structure with residual drifts resulting in out-of-plumbs.
The goal of the work is to propose an approach to provide FREEDAM structures with a self-centering capacity by studying particular devices, to be installed in beam-to-column joints or column base joints. In this paper, the attention is focused on the problem of re-centering of base plate joints studying a detail consisting in a connection located at the base of the columns of the first storey equipped with friction dampers and threaded bars. The threaded bars work as elastic springs thanks to sets of Belleville washers used to increase the deformability and to allow the opening of a gap in the connection. The main breakthrough of the proposed technology with respect to the existing literature, aside from the methodology employed for the design of the friction connection, is that the self-centering capability is obtained with re-centering elements (threaded bars and Belleville springs) which are not conceived to be extended up to the end of the column at the top storey of the building, but they have a size similar to the column splice's cover plates. The work reports the results of a preliminary experimental investigation on this joint detail which has regarded cyclic and pseudo-dynamic tests. The experimental results presented seems very encouraging towards the possible development of base plate joints with self-centering capacity combined with friction dampers.

1 INTRODUCTION

The traditional seismic protection strategy for Moment Resisting Frames (MRFs) is based, in case of destructive seismic events, on the concentration of energy dissipation at the beam ends, while columns and connections have to be over-strengthened in order to allow the full development of plastic hinges at the beam ends. To this scope, aiming to promote the plastic engagement of the greatest number of dissipative zones by properly controlling the failure mode, Eurocode 8 requires the application of members' hierarchy criteria and the design of full strength joints (accounting for random material variability effect and for strain-hardening effects). Therefore, the traditional design philosophy of seismic resistant steel frames leads to structural solutions which can be defined weak beam-strong column-strong joints. Such design solutions surely provide some advantages, such as the development of a stable plasticization and the reduction of the interstorey drifts under serviceability loading conditions but, on the other hand, they provide also several drawbacks. The most important drawback, which is common to all the traditional seismic resistant structural systems, is due to the source of energy dissipation which is part of the structural system itself. In fact, as soon as dissipative zones are constituted by sections or elements belonging to the structural system, it means that seismic energy dissipation occurs due to the yielding of these structural parts. As a consequence, after severe seismic events, the structure remains damaged and, because of permanent plastic deformations, out-of-plumb lateral deformations occurs. The magnitude of this out-of-plumb is very important in view of the actual possibility to repair the structure after a destructive seismic event.

Aiming to design structures Free from Damage, proposals of dissipative semi-continuous frames with partial strength joints able to dissipate the seismic input energy in the connecting elements avoiding the oversizing of connections and columns and preventing the beam yielding, are even more frequent. The growing interest of the scientific community to solutions adopting partial strength joints in MRFs is also reflected in last version of Eurocode 8 which has opened the door to the use of partial strength joints in MRFs allowing the dissipation of the seismic input energy by means of the inelastic behaviour of the connecting elements and, with some limitations, of the panel zones. Within this framework, a partial strength joint with friction pads appears very interesting because it leads to the prevention of any damage of the structural members and connecting elements involving only the friction pads in the dissipation of the input seismic energy. However, due to the movement of the friction pads, significant out-of-plumb deformations can remain after severe ground motions. In order to avoid this structural damage, a recentering systems can be adopted.

In this paper, in order to overcome the drawbacks of the described design strategies, a different philosophy is proposed by means of an innovative approach aimed at combining the adoption of seismic dampers with the concept of semi-continuous frame and with self-centering systems.

In particular, with reference to column-base joints equipped with friction dampers at the level of the two flanges and with the self-centering system, a preliminary theoretical and experimental analysis of the proposed joint typology have been performed carrying out tests on a full-scale column-base joint. In particular, both cyclic tests and pseudo-dynamic tests, simulating recorded historical seismic motions, have been carried out.

2 CONNECTION CONCEPT

2.1 *Concept*

Being an effective way of dissipating energy through limited motion, dry friction solutions are, in many cases, adopted in earthquake resisting supplemental damping systems. Moreover, in the last decades, the concept has been subject of study and new designs have been developed.

Tribological studies focus on the modelling of phenomena like adhesion and ploughing in friction surfaces, caused by asperities and the presence of contaminants. A discussion of the main phenomena related to friction interaction has been developed in (Latour et al., 2014; Loo et al., 2015; Ramhormozian et al., 2016).

The main proposals of the application of friction dampers in steel structures are referred to beam-to-column connections. Since the first Sliding Hinge Joint (Clifton, 2005), other typologies have been developed. In the framework of the FREEDAM Project, Latour et al., (2015) investigated a new Asymmetric Friction Connection. In this case, the damper is located on the lower flange and, under bending actions, the joint is forced to rotate around the upper T-stub and the energy dissipation supply is provided by the slippage of the lower beam flange on the layers of friction materials.

A beam-to-column typology introducing two dampers at both flanges were also tested in (Latour et al., 2015; Iyama et al., 2009).

The application of friction dampers in the column base connection of steel structures is not widely investigated. Two typologies for the base connection are proposed by McRae et al. (MacRae et al., 2009), while in (Borzouie et al., 2015) the study of the efficiency of the dissipation of seismic energy through column base solutions has been performed carrying out a series of experimental works on different low damage steel base connection. Within the work, two new designs are tested: the weak axis aligned asymmetric friction connection, where friction surfaces are parallel to the web on plates outstanding from the column flange, the strong axis aligned asymmetric friction connection, where friction surfaces are parallel to the column flange.

2.2 *Recentering systems*

A recentering capable system is held by being the structure’s tendency to return towards the origin during the seismic event. Otherwise known as restoring capability, this phenomenon is identified by the current codes as a fundamental requirement for seismic isolation systems. The existence of forces acting towards the origin increases the system’s restoring capability. In the same way, forces acting away from the origin will, on the other hand, decrease this capacity, such as hysteretic forces and friction forces in sliding bearings.

Practical cases of self-centering systems usually include bar or tendon-like components, which can be applied on joints or in entire elements. Khoo et al., (2013) proposed the addition of friction ring springs to the SHJ, resulting in a flag-shape behaviour of the connection, although this typology is limited by its cost. A similar approach in terms of recentering was made by Xu et al. and by Zhang et al., (2016) for which the recentering component is done by the installation of rods, located on the beam, rather than solely on the joint. In the first, the introduction of an "active link" is done and the linkage to the beam, in both ends, is achieved by pretensioned rods, as the second, a set of rods goes through the entire segment of the beam and attached in the joint sections, while a bolted web friction device is also included. The designs, although promising, demand further testing, in order to make them viable to put into practice.

Base connections have also been developed in (Chi & Liu, 2012) and in (Fisher & Kloiber, 2006) which use post-tensioned rods anchored to the column foundation. The aim is to ensure the possibility of movement and stress the rods within their elastic capacity. However, the proposed solutions, based on the anchoring of the rods to the foundation, can be less effective in a replacement situation.

Friction systems can show a self-centering ability. However, such capability might not be sufficient and an additional component is needed to restore the original form of the structure. To solve this problem, an adaptable recentering system can be adopted. Practically, the application of a source of a stabilizer force can be a solution. This leads, primarily, to the increase of the force necessary to cause displacement in the friction interfaces. When displacement happens, and while it increases, the existing stiffness of the both systems induce an increase of the destabilizing force in the same manner. Finally, at the end of each cycle, being the external forces equal to zero, the kinetic and potential forces in the system are controlled by the presence of the stabilizing component. Graphically, a "flag-shaped" loop can be seen as a sufficiently close representation of the cycles (Fig. 1). A shift in the force axis is observed in the otherwise parallelogram-shaped behaviour. Additionally, an increase in the stiffness will be observed, due the restoring system's contribution.

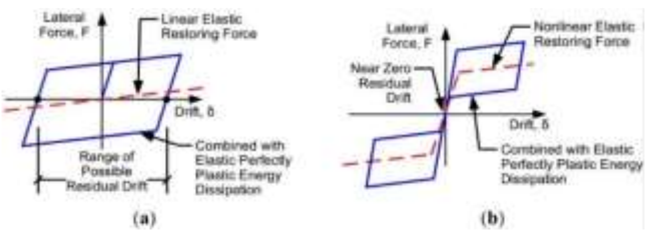


Figure 1. (a) Restoring force not full self-centering; (b) Full self-centering by mens of nonlinear elastic restoring force.

2.3 *Proposed solution*

Being the design and testing of a free from damage column base steel connection the main objective of this work, both friction plates have been used and a recentering system has been adopted.

In particular, the proposal consists on the cut of the column close to the base section and on the connection of the two parts by means of sets of plates fastened by bolts to the web and flanges (Fig. 2).

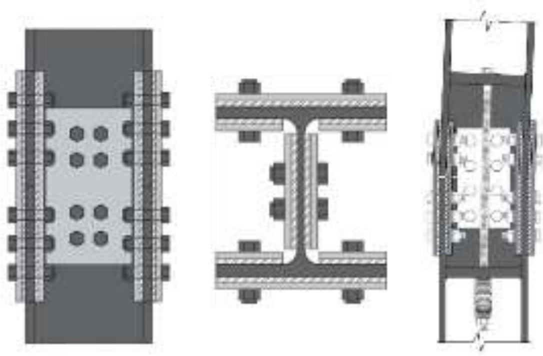


Figure 2. (a) Concept of the proposed solution

The flange plates were applied in both outer and inner parts, as for the web the plates were used in both sides as well. To allow the gap opening, slotted holes have been designed on the column flange and web. Between the steel plates and the column, friction pads have been inserted.

Regarding the recentering behaviour, threaded bars, acting as long pretensioned bolts, have been adopted (Fig. 2b). However, if threaded bars do not possess low enough stiffness and high enough resistance simultaneously to allow the gap opening without engaging in plastic range, a system of disks arranged in series and parallel to form a spring has been introduced.

With reference to one-story subassembly depicted in Fig. 3a, the behavior of the whole system (connection, with flange and web friction pads and recentering bars, plus column) can be modelled by means of the mechanical model depicted in Fig. 3b. The rotational spring Cb accounts for the flexural stiffness of the column branch of length equal to l_0 (Fig. 3a), given by:

$$K_{Cb} = \frac{3E_s I_c}{l_0} \quad (1)$$

where E_s is the steel modulus of elasticity and I_c is the moment of inertia of the column profile. The translational spring F_f models the friction pads on the column flange. The stiffness of this component can be assumed infinite up to the achievement of the slippage force and equal to zero when this value is reached. Similarly, F_w models the friction pads on the column web. Also in this case, the stiffness is infinite up to the achievement of the slippage force and equal to zero when this value is reached. The translational spring F_{tb} models the axial behavior of the threated bars which work in series with the disk spring, modelled by F_{ds}. The stiffness of the threated bars is given by:

$$K_{ds} = \frac{n_{par}}{n_{ser}} K_{ds1} \tag{2}$$

Regarding the disk springs, their stiffness can be evaluated by means of the following relationship:

$$K_{ds} = \frac{n_{par}}{n_{ser}} K_{ds1} \tag{3}$$

where n_{par} is the number of disk spring in parallel, n_{ser} the number of disk spring in series and K_{ds1} is the stiffness of each disk spring.

In Fig. 4, typical flag shape relationship between the column moment in correspondence of the cut section and the drift angle is depicted. The moment M_2 represents the decompression moment which corresponds to attainment of the slippage force in all friction pads.

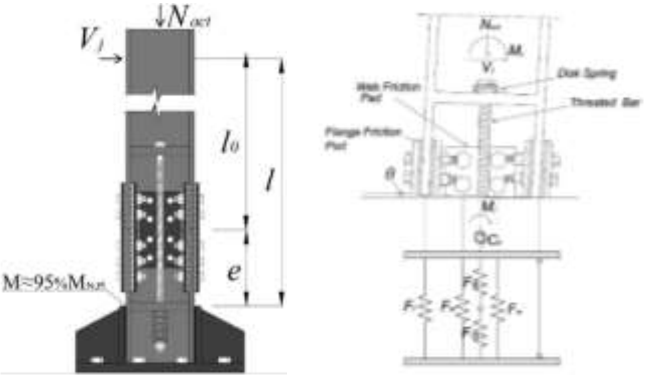


Figure 3. Schematic view of the proposed solution

The first branch is characterized by the springs modelling the friction pads with infinite stiffness and, therefore, the rotational stiffness of the whole system is coincident with that of the rotational spring K_{Cb}. In the second branch, corresponding to the gap opening, the slippage of the friction pads arises and the rotational stiffness of the system is given by the springs in series of the threated bars, disk springs and column in bending.

Therefore, the rotational stiffness of the second branch is given by:

$$K_2 = \frac{1}{\frac{1}{K_{Cb}} + \frac{4}{h_c^2}\left(\frac{1}{K_{tb}} + \frac{1}{K_{ds}} + \frac{l_{tb}}{E_S A_C}\right)} \tag{4}$$

where h_c is the column section height and the last term in round brackets is the axial stiffness of the column part on which the threated bars act. The branches 3 and 4 are characterized by the same stiffness of the branches 1 and 2, respectively.

The moment M_0 represents the share of the decompression moment due to axial load in the column and to the pre-load of the threated bars, equal to:

$$M_0 = (F_{tb} + N_C)\frac{h_c}{2} \tag{5}$$

The moment M_1 represents the contribution to the moment due to friction pads, equal to:

$$M_1 = F_f\left(h_c - \frac{t_{fc}}{2}\right) + F_w\frac{h_c}{2} \tag{6}$$

where t_{fc} is the thickness of the column flange.

From design point of view, the flag shape of the moment-rotation curve can be obtained imposing that:

$$M_0 - M_1 \geq 0 \Rightarrow F_{tb} \geq F_f\left(2 - \frac{t_{fc}}{h_c}\right) + F_w - N_c \tag{7}$$

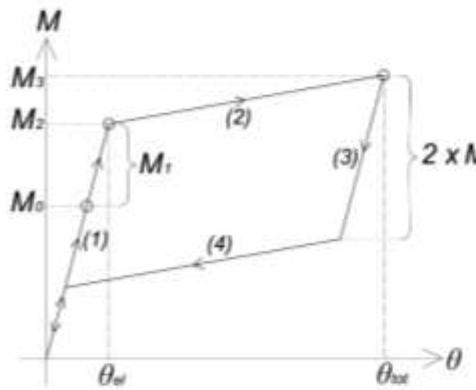


Figure 4. Moment-drift angle relationship

3 DESIGN OF THE SPECIMENS FOR EXPERIMENTAL TESTS

3.1 Concept

The first step in designing the specimens to be submitted to cyclic and pseudo-dynamic tests, consisted in the definition of the design bending moment, shear and axial load. Regarding the axial load, a value equal to 25% of the squash load has been chosen. For the bending moment, a design value equal to 95% of the plastic bending moment of the column section reduced for accounting the axial load interaction, has been assumed. The shear load derives from the structural scheme. Therefore, starting from a choice of column section HEB240 and steel resistance class S275, the following design values have been considered:

$$N_d = \nu\, N_{pl} = 0{,}25\, N_{pl} = 728{,}75\, kN \tag{8}$$

$$M_d = 0.95 M_{pl} \frac{1-\nu}{1-0.5\theta} = 198{,}6\ kNm \quad \Leftarrow \quad \theta = \frac{A_c - 2 b_c t_{fc}}{A_c} = 0{,}23 \leq 0{,}5 \qquad (9)$$

$$V_d = \frac{M_j}{l_0} = 128{,}1\ kN \qquad (10)$$

where l0=1.55 m is the distance between the horizontal action at the top of the column and the cut section (Fig.3a). On the basis of the shear design load Vd, firstly, the web component has been designed imposing that the slippage force on the web has to resist the applied shear load. All plates, for web and flange connection, are S275 steel class. The friction pads have been chosen according to the results on friction material obtained in (Latour et al., 2014). A friction coefficient μ=0,6, has been assumed. Considering four bolts for both the upper and lower sides of the web connection, the necessary pre-load Fwp, for each bolt, was:

$$V_d = F_w = \mu\, F_{wp}\, n_b\, n_s \Rightarrow F_{wp} = 26{,}7\ \ kN \qquad (11)$$

and M14 HV bolts of 10.9 class was chosen.

In order to design the re-centring threated bars, as shown by Eq. (7), the force in the bars depends by the slippage force of the flange friction pads. Therefore, imposing together with Eq.(7) also the global equilibrium between internal and external moment in correspondence of the cut section, the following system can be used for designing both F_{tb} and F_f:

$$\begin{cases} F_{tb} - F_f \left(2 - \frac{t_{fc}}{h_c}\right) \geq F_w - N_c \\ F_{tb}\ \frac{h_c}{2} + F_f\ \left(h_c - \frac{t_{fc}}{2}\right) = M_d - (F_w + N_c)\ \frac{h_c}{2} \end{cases} \qquad (12)$$

For seek of simplicity, if we assume the lever arm of the Friction force of the column flange friction pads equal to h_c, system (12) leads to the following simple design formulation for the threated bars:

$$F_{tb} \geq \frac{M_d}{h_c} - N_c \quad \Rightarrow \quad F_{tb} \geq 98{,}6\ \ kN \qquad (13)$$

For the specimens, two M20 threaded bars, having the maximum capacity of 155,9*kN* of pre-loading, are adopted for the recentering system. Each bar preload has been chosen equal to 100 kN.

Therefore, system (12), provides the following value of the design slippage force of the column flange friction pads:

$$F_f = \frac{M_d}{h_c} - \frac{1}{2}\ (F_w + N_c + F_{tb}) \Rightarrow F_f = 298.9\ \ kN \qquad (14)$$

Considering four bolts for both the upper and lower sides of the column flange connection, the necessary pre-load F_{fp}, for each bolt, was:

$$F_f = \mu\, F_{fp}\, n_b\, n_s \quad \Rightarrow \quad F_{fp} = 62{,}3\ \ kN \qquad (15)$$

Also in this case, M14 HV bolts of 10.9 class was chosen, having a maximum capacity of 73,2 *kN* of pre-loading.

The last step of the design procedure consists on the design of the disk springs. Assuming a maximum rotation for the joint equal to 40*mrad*, a maximum strain for the recentering system equal to 4,8*mm* is attended. Adopting disk springs with diameter equal to 45 mm, thickness equal to 5 mm and height of the internal cone equal to 1.4 mm, three disk springs in parallel are necessary for covering the bar yielding force. The resistance of each disk spring is about 79,77kN, while the stiffness (K_{ds1}) is about 79,79kN/mm. Considering the maximum displacement allowed by the threated bars in elastic range, Eq. (3) provides a minimum number of 7 disk springs in series with a global stiffness K_{ds}=35.36 *kN/mm*.

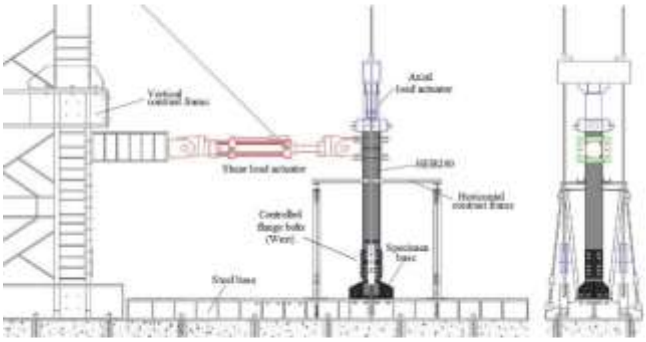


Figure 5. Experimental layout

4 CYCLIC EXPERIMENTAL TESTS

The testing equipment is depicted in Fig. 5. Two actuators have been used: the first one, at the top of the column is a Moog Actuator (Maximum Load 3000 kN) governed under load control in order to apply the axial load in the column, the second one is an MTS 243.35T actuator, with a maximum load capacity of 385 kN in compression and 240 kN in tension and a piston stroke of 1016 mm, controlled under displacement control in order to apply a cyclic shear force at the top of the column.

Regarding the measurement devices, a torque sensor Futek TAT430 and four load cells Futek LTH500, holding a maximum capacity of about 222kN, applied in both recentering bars and in two of the four bolts of one of the sides of the column have been used (Fig. 6c). Additionally, displacement transducers Luchsinger type LDT (max. 50mm) have been adopted in order to measure the vertical displacements in both column sides (Fig. 6c).

Figure 6. Specimen before the test

Regarding the bolt tightening procedure (on the basis of the available information coming from friction tests (Latour et al., 2014)) the load was increased to account for the immediate pre-tension, and a minimum of 10% is to be added to the bolt loads. Thus, a torque of 180kNm was applied in the flanges and 60kNm in the webs, resulting an approx. force of 70kN and 30kN, respectively. The pre-loading of the threated bars was reached by direct observation of the load cells output, and no extra load was exerted.

For the actions, the axial force is the first to be applied and is constant throughout the test, followed by the cyclic shear load. The shear load follows the loading protocol present in ANSI-AISC 341-10 (2010). This protocol is conducted by controlling the interstory drift angle (θi-s), imposed on the test specimen according to AISC 358-16.

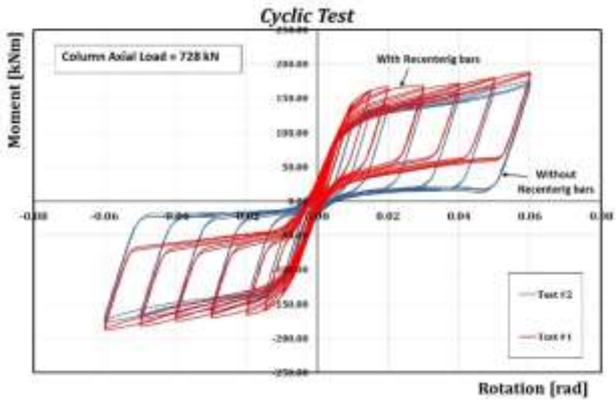
Four cyclic tests have been performed by varying the axial load in the column and the presence or not of the recentering threated bars. In particular, axial loads equal to 25% and 12,5% of the squash loads N_p of the column profile have been applied. Regarding the tests with lower values of the column axial load, the total axial load in the recentering bars has been increased to 280 kN, compatible with the pre-loading capacity of the threaded bars but not sufficient to respect Eq. (7) for guaranteeing the flag shape behaviour.

In table 1, a summary of the main values related to the loading condition of the specimens is given.

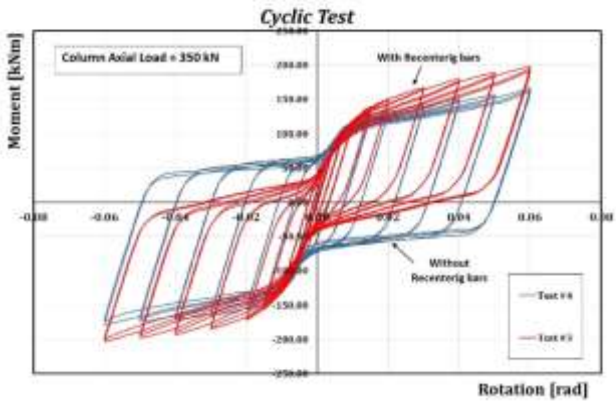
In Fig. 7, the hysteretic curves provided by the experimental tests are depicted. In particular, in Fig. 7a the experimental tests with higher axial load are depicted while Fig. 7b show the tests with lower value of axial load. The general behaviour of connection matches the expected, resulting a flag-shaped curve with almost full-recentering behaviour. It can be observed that the threated bars play an important role.

Table 1. Main loading values applied to the specimens

Test	Type	Load [kN]	Bar Preload [kN]	Preload Web bolts [kN]	Preload Flange bolts [kN]
1	Cyclic	728	200	27	62
2	Cyclic	728	0	27	62
3	Cyclic	365	280	30	114
4	Cyclic	365	0	30	114
5	Pseudo	728	200	27	62
6	Pseudo	728	0	27	62
7	Pseudo	728	200	27	62



a) Column Axial Load = 728 kN



b) Column Axial Load = 350 kN

Figure 7. Experimental layout

The design conditions appear accurate. The Test 1 of Fig. 7a highlights that, according to the design condition, the flag shape behaviour has been obtained while the Test 3, in which the preloading of the threated bars is about 48% of the minimum value necessary for guaranteeing the flag shape behaviour, evidences a not completely developed flag shape behaviour even though the recentering effect of the threated bars appears important.

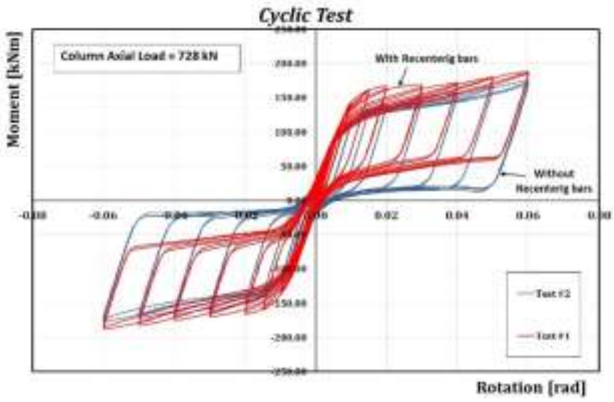
This is clear comparing the results of the Test 3 with that of the Test 4 in which threated bars are not used. Comparing Fig. 7a with Fig. 7b, it can be recognised that the role of the recentering bars is even more important when the column axial load is low due to the reduction of the recentering action of the column axial load.

5 PSEUDODYNAMIC TESTS

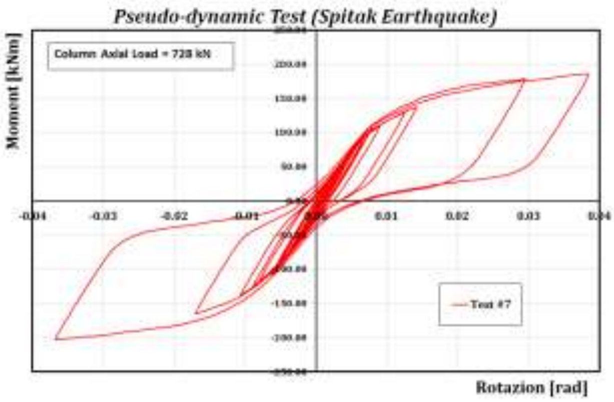
Aiming to verify the ability of the proposed column base connection to dissipate the energy and to recenter the structure after severe earthquake, pseudo-dynamic tests (PsD) have been performed at the laboratory of materials and structures of the University of Salerno. This testing method combines an on-line computer simulation of the dynamic problem (accounting for damping and inertial effects) with experimental data regarding restoring forces and corresponding displacements due to quasi-static application of loads, to provide realistic dynamic response histories even in case of non linear behaviour of severely damaged structures (Shing et al., 1984). It uses essentially the same equipment as conventional quasi-static tests, in which prescribed load or displacement histories are imposed on the specimen by means of servo-hydraulic actuators (Fig. 5). The structure to test has been idealized as a discrete-parameter system consisting of one degree of freedom, controlled by the actuator.

The classical equation of motion is solved by means of a direct step-by-step integration scheme (Hilber et al., 1977) in which the mass and the viscous damping properties of the structures are modelled analytically while the displacements, and consequently the restoring forces developed by the structure, are measured with the external transducers positioned on a reference frame.

In the experimental test the MTS hydraulic actuator was used to apply the displacement history to a system of fictitious mass assumed equal to 74t. The test was carried out assuming no viscous damper and applying a loading velocity equal to 0.1 mm/s.



a) Kobe Earthquake

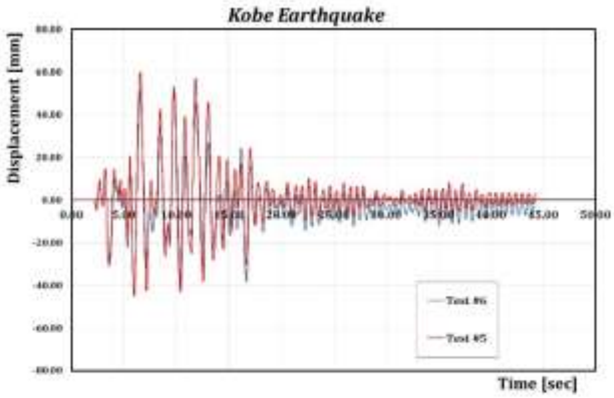


b) Spitak Earthquake

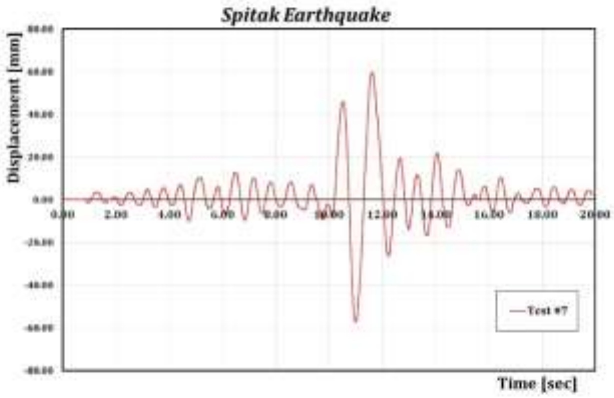
Figure 8. Moment-Rotation curves of specimens submitted to pseudodynamic tests

In order to perform the tests, the Kobe (Japan, 1995) and Spitak (Armenia, 1988) earthquake records were selected as ground motion. A record scale factors equal to 1.4 (PGA=0.35g) for the Kobe earthquake and equal to 1 (PGA=0.199g) for the Spitak earthquake, were considered.

In Fig.8 the moment rotation plot of the pseudo-dynamic tests are reported. These pictures confirm the recentering behaviour of the proposed column base connections testified by the flag-shaped curve as already evidenced by the cyclic tests. Also in this case, the comparison between the moment-rotation curve of the column base connection with and without the recentering threated bars (Fig. 8a) highlights the important role of the adopted bars with the belleville disk springs. This effect is also evidenced by the reduction of the residual displacement after the earthquake. In Fig.9 the time-history of the displacements of the top of the column are shown for the three pseudo-dynamic tests. It can be observed that the column with the proposed base connection with recentering bars is characterized by a residual displacement after the earthquake practically negligible.



a) Kobe Earthquake



b) Spitak Earthquake

Figure 9. Displacement Time-history of specimens submitted to pseudodynamic tests

6 CONCLUSIONS

In this paper, a structural solution of base plate joint equipped with friction dampers and threaded bars in order to solve the problem of the re-centering of the structures has been proposed aiming to perform structures free from damage. In particular, the designed base plate joints tested under cyclic and pseudo-dynamic loads, evidences that, according to the design requirements, the threaded bars work as elastic springs thanks to sets of Belleville washers used to increase the deformability and to allow the opening of a gap in the connection. The experimental test performed at the STRENTH laboratory of the University of Salerno evidenced a flag-shaped moment-rotation curve of the proposed column base connections with friction pads and recentering bars which are able to dissipate the seismic input energy by means of stable cycles and lead to a residual displacement after the earthquake practically negligible.

This preliminary experimental investigations have provided very encouraging results, suggesting to undertake a wide experimental and analytical research project aimed at the investigation of the design issues to be completely clarified before the practical application of this design strategy.

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