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Experimental investigation of a new steel friction device with link element for seismic strengthening of structures

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Abstract. In the present work a new friction device, with a set of single or double rotational friction flanges and a link element, is described and tested. The mechanism may be applied for the strengthening of existing r/c or steel buildings as well as in new constructed buildings. The device has selectable variable behavior in different levels of displacement and an interlock meαchanism that is provided by the link element. The link element may be designed to lock at preselected level of displacement, offering in this way an extra safety reserve against strong earthquakes. A summary of the existing literature about other similar mechanisms is initially presented in this paper. The proposed mechanism is presented and described in details. Laboratory experiments are presented in detail and the resulted response that proves the efficiency of the mechanism at selectable levels of strength capacity is discussed. Drawings of the mechanism attached to a r/c frame with connection details are also included. Finally a dynamic analysis of two r/c frames, with and without the proposed mechanism attached, is performed and the resulted response is given. The main conclusion is that the proposed mechanism is a cheap and efficient devise for the improvement of the performance of new or existing framed buildings to seismic loads.

Keywords: multi-storey frames; bracing; variable strengthening; metal friction device; experimental tests; cyclic loading; link element; numerical approach

1. Introduction

The construction and the use of multi-storey buildings for housing educational, commercial and residential activities, has increased since the beginning of the 20th century. These buildings have been used continuously over these decades resulting to the existence of a building stock with various strength levels. Almost all these buildings have a significantly very low strength compared to that specified by the modern codes. Due to the high living standards of the contemporary era

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there is usually a desire for the strengthening of the load carrying system of these buildings. For this purpose many construction techniques and materials have been developed. In the present work a novel device (presented in Fig. 1), is experimentally tested and partially simulated. This mechanism is suggested for use in new constructed buildings as well. By using this device the beam – column frames can be easily strengthened at many predefined and desired levels. This device can be easily embodied in Reinforced Concrete (R/C) or steel frames. The device utilizes friction elements with the capacity of using a single or double set of friction flanges and an interlock mechanism. The friction capacity is directly proportional to the pres-tress force that is applied by rotating four bolts. The interlock link element incorporated at the device may yield at a predefined level of displacement and horizontal force (Fig. 2). This device together with a surrounding frame were constructed on a 1:2 scale and tested at the laboratory. The recorded response together with the post-processed records are presented and discussed. Finally the new frictional device is modeled on a frame building and its contribution to the resisting capacity of the building against seismic loads is proven.

2. Literature review

The idea of using friction devices for increasing the load carrying and energy dissipation capacity of frames is not new. Various types of similar devices were proposed over the last decades. Since early 80s Pall and Marsh (1982), have present a friction damped mechanism for the mechanical dissipation of the vibrational energy at multi-storey buildings that are subjected to strong earthquakes. Since 80s till nowadays this mechanism was applied in many multi-storey buildings, located at high seismicity areas. Friction devices of various types were extensively tested and studied last years by Rojas *et al*. (2005), De la Cruz *et al*. (2007), Apostolakis and Dargush (2010), Lopez-Almansa *et al*. (2011), Rodgers *et al*. (2012) indicating thus the need for this type of mechanisms. Filiatrault and Cherry (1988), have presented a friction device and compared it to base isolation mechanisms for the control of a ten-storey frame. It was found that for an earthquake whose energy is well distributed over a relatively broad frequency band, both systems offer comparable performances. However, for earthquakes whose energy content is concentrated at the low frequency end of the spectrum, the performance of the structure, equipped with friction devices was shown to be significant superior to the performance exhibited by the same structure retrofitted or designed with base isolation. Zhang *et al*. (1989), presented an evaluation of the effect of added viscoelastic (VE) dampers in reducing earthquake response of multi-storey steel frame structures. In analytical models was shown that that VE dampers can be effective in structures subjected to earthquake excitations. It was found that the addition of VE dampers results in a significant increase in modal damping ratios in all modes considered. Filiatrault and Cherry (1990), presented a parametric study on multistory friction-damped braced frames, whose results were used to construct a general design slip-load spectrum for a quick evaluation of the total optimum slip shear in multistory buildings. The spectrum takes into account the properties of the structure and of the ground motion anticipated at the construction site. The availability of this slip-load design spectrum is necessary for greater acceptance of this innovative friction – damped structures. Pekau and Guimond (1991), tried to control seismic response of eccentric structures, where lateral-torsional coupling characterizes the behaviour, by friction dampers. The need was demonstrated to tune the devices with respect to both the stiffness of the braces and the slip load of the devices. Properly tuned, the friction dampers dramatically reduce maximum response compared to the eccentric response of unbraced structures. For even highly eccentric structures, it is possible to limit the maximum response to a level equal to or below that of the corresponding unbraced symmetrical structure. These conclusions were also demonstrated in three-dimensional building systems. The seismic response of braced frames with and without friction dampers was studied by Colajanni and Papia (1995). The reliability level of friction damped braced systems (FDBS) and of ordinary cross-bracing systems (CBS) having slender braces was investigated by step-by-step analyses of their seismic responses. The bracing systems were inserted into surrounding frames without lateral stiffness, made of axially inextensible elements with hinged joints. The results confirmed the correctness of the provisions of several codes for CBS, and showed the field of practical use in which the FDBS proves to be advantageous in reducing design seismic forces. In a comprehensive review by Symans and Constantinou (1999), on semi-active control systems for seismic protection of structures was mentioned that friction control devices may be reasonably described by simple phenomenological models. Also by the experimental testing described in this paper is clearly demonstrated that the semi-active control method has the potential for improving the seismic behavior of large scale civil structures. A new friction damper device for steel frames was proposed by Mualla and Belev (2002). The damper main parts are the central (vertical) plate, two side (horizontal) plates and two circular friction pad discs placed between the steel plates. The tests and the numerical studies reported clearly demonstrate that passive response control systems based on new Friction Damper Device, present a viable alternative to the conventional ductility-based earthquake –resistant design both for new construction and for upgrading existing structures. The device can be economically produced and installed in structural frames to protect buildings from structural and non-structural damage in moderate and severe earthquakes. Wu *et al*. (2005), develop a new type of Pall frictional damper (PFD). This improved damper (IPFD) was compared with the original PFD, with the first one offering some advantages in terms of ease of manufacture and assembly. The IPFD is cheaper and easier to analyze than the OPFD. A new Self Centering Energy Dissipative bracing system was presented and studied by Christopoulos *et al*. (2008). This bracing system was developed to undergo large axial deformations without structural damage, while providing a stable energy dissipation capacity and a full self-centering response within the targeted design drift. After the mechanics were described and the equations governing the response of the SCED were defined, a series of component and system level experimental validations that demonstrate the behavior of this system under simulated seismic loading were presented. Finally a rapid seismic rehabilitation strategy based on cable bracing with COuples REsisting Damper (CORE Damper) was studied by Kurata *et al*. (2011). The proposed system uses tension-only elements and eliminates undesirable global and local buckling. The prototype design of the tension-only system was explored in analytical studies using both advanced and simplified models and its stability and high performance was verified during proof-of-concept tests.

A critical review of the literature concludes that during the last 30 years many friction devices that provide supplemental seismic energy dissipation and/or strength capacity were tested and proposed. However there is an apparent lack of a mechanism where predefined strength reserves and energy dissipation capacity can be easily and effectively provided. The proposed mechanism presented and tested herein is a cheap and effective device for the provision of supplemental energy dissipation and strength capacity by fully controlling the desired performance improvement of existing and new constructed frame buildings. This is achieved by the appropriate tightening of four bolts and selection of the cross section dimensions and the gap of the link element. The proposed mechanism is presented and described in details. The laboratory experiments are presented in detail and the resulted response that proves the efficiency of the mechanism at selectable levels of strength capacity is given. Drawings of the mechanism attached to a r/c frame with connection details are also included. Finally a dynamic analysis of a r/c frame, with the proposed mechanism attached, is performed and the resulted response is discussed.

3. The proposed frictional anti-seismic device

3.1 Description

In this paper, a new rotational friction device, with variable behavior is experimentally validated. The innovation on this mechanism is the type of link element that is provided. This device was simulated analytically in Papadopoulos (2010), in order to check its efficiency and in present paper this device is experimentally tested. The device (shown in Fig. 1) is placed to the cross point of four diagonal steel braces and can be used to increase the strength and dissipation capacity of R/C and steel frames. The variable behavior of the device is achieved by its lock, in a desirable level of displacement, offering this way, strength increase and limitation to the displacements of the strengthened frames. In many cases, if these displacements were not limited, greater damages or whole collapse may be expected. In this way, a second level of protection is provided, particularly in case of strong earthquakes. The proposed strengthening device is comprised by four diagonal steel elements with circular cross section. These elements are anchored at the beam column joints. The device may be used at the same joints along the height of the frame or at various locations.

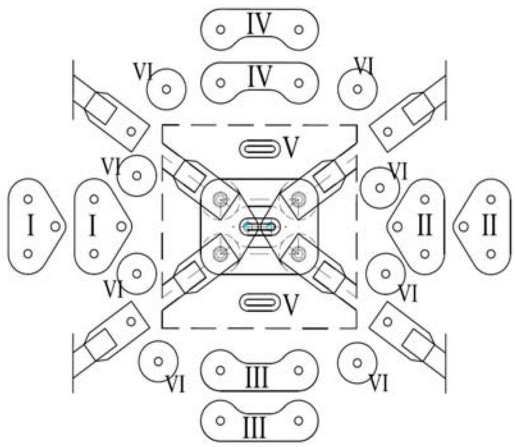


Fig. 1 Presentation of the friction device and its components

At the convergence point of the diagonal steel braces there is the friction device that is formed in the shape of a rectangle. At the corners of the rectangle the steel elements cover each other. At these points special flanges are inserted and the friction device is thus formed. By the use of special pre-stressing bolts at the corners of the device the desired level of friction is applied and the desired strengthening level is achieved at the frames. The contribution of the device is also increased by the use of a single or double set of steel flanges. The mechanism is equipped with a device of additional strength and stiffness. For this reason a link element is used at the middle of the vertical legs of the rectangle. This link element is activated after a desired level of deformation of the strengthened frame has reached and provides the desired level of supplemental strengthening.

The individual elements of the proposed steel device are described below (Fig. 1):

(1) Elements I: two external elements of a triangular shape
(2) Elements II: two external elements of a triangular shape
(3) Elements III: two elements for the connection of the two lower diagonal braces.
(4) Elements IV: two elements for the connection of the two upper diagonal braces.
(5) Elements V: two elements for the connection of the elements I and II (link elements).
(6) Synthetic material that is inserted into the connections between triangular elements I and II, and elements III and IV, in order to develop the desired demand friction.

The advantages of the proposed device are distinguished bellow:

(1) By the use of the proposed device the load carrying capacity of the strengthened frame is increased by a constant, predefined, level through friction. Also by the use of the link element a supplemental strength and stiffness is provided after a predefined level of deformation. When this link element is activated, the device is locked, offering thus additional stiffness/resistance and limitation of the structure's displacement.
(2) The strengthening level can be easily adjusted and changed during the years of existence and operation of the structure. This can be achieved by applying the appropriate torsional moment to the bolts of the mechanism. Also by selecting the appropriate length and section of the link element is possible to predefine the deformation level after which the link element is activated as well as the desired increase of the quantity of the supplemental strength and stiffness.
(3) The device is capable to fully perform in both directions when is subjected to cyclic loads and the response is symmetrical during each half of the imposed cyclic load. The strength increases, due to the friction component and due to the link element.

This mechanism may be applied to new constructed buildings as well as existing ones. In new constructed buildings the choice of the bay where the mechanism will be used, is guided by the known criteria of regularity in plain and along the height of the building. In existing buildings the choice of the strengthened bays is related with:

- accessibility criteria (windows and/or door openings),
- full cover of the beam – column bays with infill walls
- not junction of more than one braces to a joint
- regularity criteria in plain and along the height of the building.

In this device, as well as in all similar devices, the resulted stress influences the beam column joins when the braces are attached to them. For new constructed buildings this influence can be easily modeled and taken into account by appropriate design of the joins and the ends of the beams and columns, framing into the joint. For existing buildings, simple modeling techniques may be applied. Care should be taken in order to ensure that the developed bracing force could be securely withstood by the joint and by the elements framing into the joint. For this purpose is suggested the use of steel angle elements with one leg attached to the column end and the other leg to the beam end. By the appropriate design of the steel angle element, the developed bracing forces can be withstood safely. In both cases (existing and new buildings) during the modelling of the structural elements and the brace, framing into the joint, the surface stresses of the metal angle should be applied to the joint for the evaluation of either the remaining safety level or the need of applying further strengthening techniques.

3.2 Stages of operation

Bellow are described the stages of operation of the proposed device during the first half of an imposed cycle. As was mentioned above the response of the device, during the each half of the imposed cyclic load, is symmetrical.

Stage 1: The device is off (position of immobility). Here, the flexural moment that develops on the rotary connection points is less than the friction rotation moment MF, which is developed by the clamping force on the rotational connections and the inserted synthetic material. Therefore, the rotary connections of friction have not yet been activated and the steel diagonal braces function in a pure elastic state, where their maximum axial forces are less than the yielding axial forces (in tension/compression), respectively (i.e., lines O – P1 of the Fig. 2).

Stage 2: The device is on (operation of the mechanism). The flexural moment that develops on the rotary connection points is equal with the friction rotation moment. During this stage, the rotary movement of the connections is permitted, while both the flexural moment M_F and, the axial forces of the diagonal steel braces are constant (line P1 – P2). It is worth noting that on the rotary connections, friction forces develop in a similar way to the disc brakes on vehicles. In other words, the ‘yielding point P1’ is due to rotational movement, which occurs at the specified moment M_F and not to the yielding of the material.

Stage 3: The device is locked by the link element. Therefore, the diagonal braces are fully activated. More specifically, the locking of the device causes an increase of the tensile axial force of the bar and the lateral strength of the frame is increased to the maximum value (i.e., line P2 – P3 of Fig. 2). Until this stage the imposed displacement is increased.

Stage 4: In this stage the imposed displacement changes direction. The resisted force is reduced until the point of zero force. The point of zero force corresponds to a displacement slightly lower than the displacement of maximum force.

Stage 5: While the imposed displacement is increased the resisting force of the device is increased the same way as in stage 1 (in the opposite direction), until the maximum static friction value is overpassed.

Stage 6: After the overpass of the static friction value, the contribution of the device is constant to the strength level of stage 2 (with opposite sign). The half cycle ends when the imposed displacement is zeroed.

After that stage 6 the device operates in second half cycle of displacement like in stages 2 to 6 until the cycle is completed. The response of the proposed mechanism is presented in more details in Fig. 2, C1-C3.

4. Experimental test set-up

The tests that are described bellow were performed in order to study the parameters of the response of the proposed device that are related with:

- The level of pre-stress force at the friction flanges
- The performance of the link element after the lock of the device
- The differences on the response of the device when single or double set of flanges are used

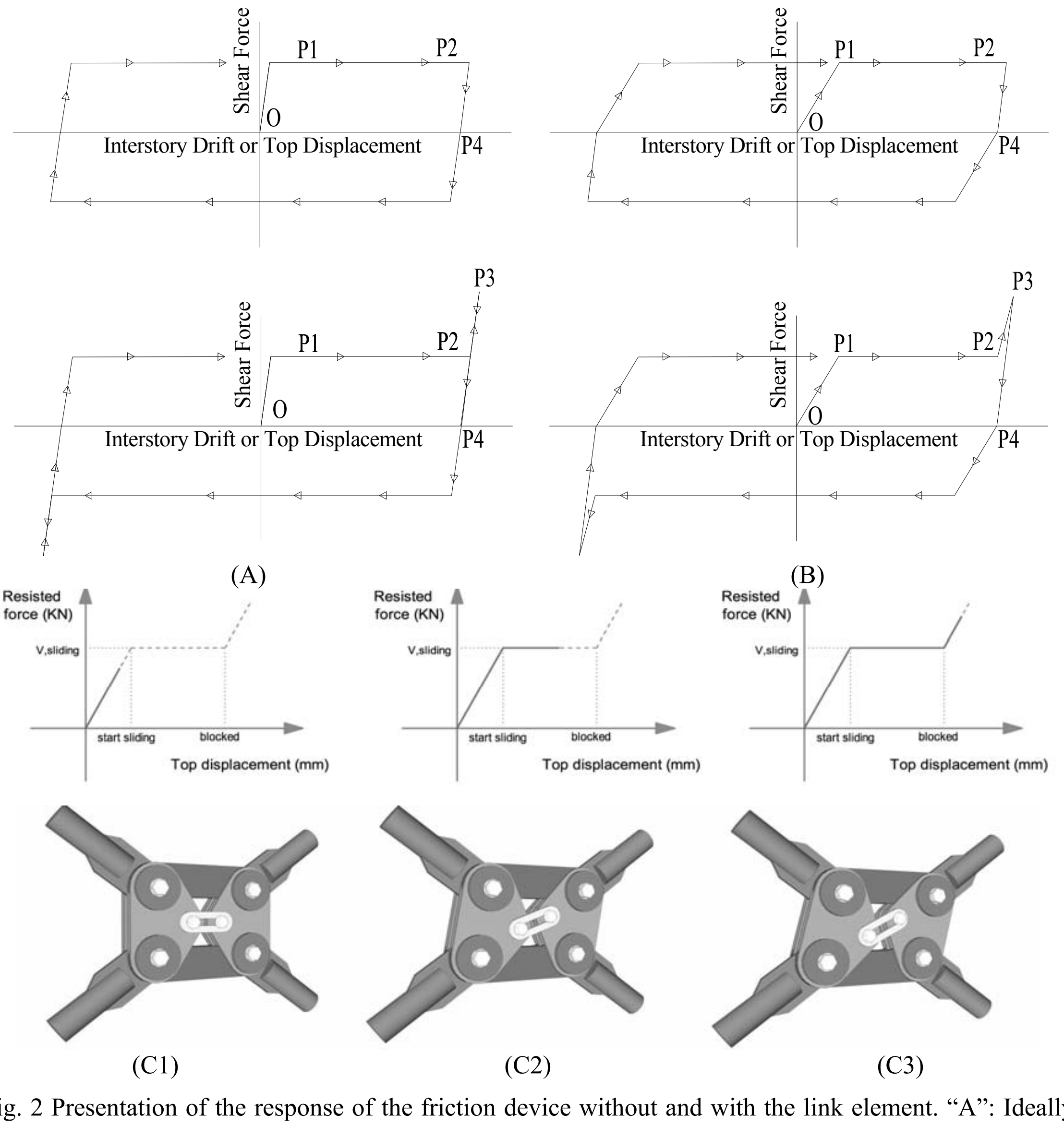


Fig. 2 Presentation of the response of the friction device without and with the link element. "A": Ideally perfect response of the device, "B": Expected response due to the existence of gaps at the locations of the rotational hinges, "C1-C3". Different stages of operation for the mechanism (C1-C2 No link interlock l_{link}=lo, C3 interlock of the link element l_{link}>lo).

The proposed device was connected to a rectangular steel frame with diagonal steel braces. The rectangular steel frame was used in order to simulate the surrounding beam - column frame. This frame was constructed with four rotational hinges at the four corner nodes. There was not resisting capacity at these four hinges. This was also certified by performing some tests without pre-stressing the friction device and without using the link element. The use of a surrounding steel frame with free rotational hinges at the corners was decided in order to avoid its inelastic deformation and the damages to the beams and columns. This way the same frame was used in all tests. Due to the existence of rotational hinges, without resistance, at the nodes of the surrounding frame the resisting force resulted only by the activation of the frictional steel device and the link element whenever was activated. This device was located at the cross point of the diagonal braces. In order to ensure the out of plane stability of the frame, four supports (supplied with regulatory screws) were provided at the base beam of the tested frame. Four diagonal braces were used for the connection of the surrounding frame with the friction device. The experimental test setup is shown in Figs. 3 and 4. The steel that was used was normal strength construction steel. It is noticed that the proposed device may be used for the strengthening of steel and reinforced concrete frames.

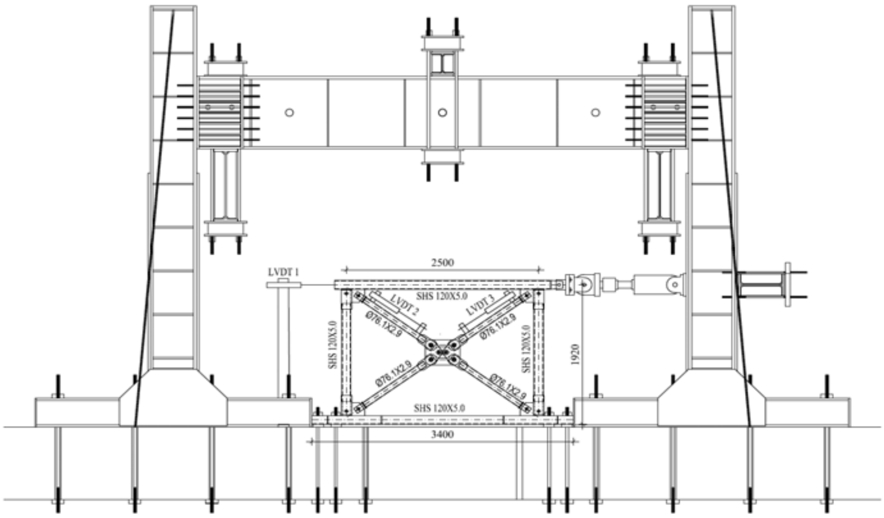


Fig. 3 Experimental test set-up with LVDTs in position

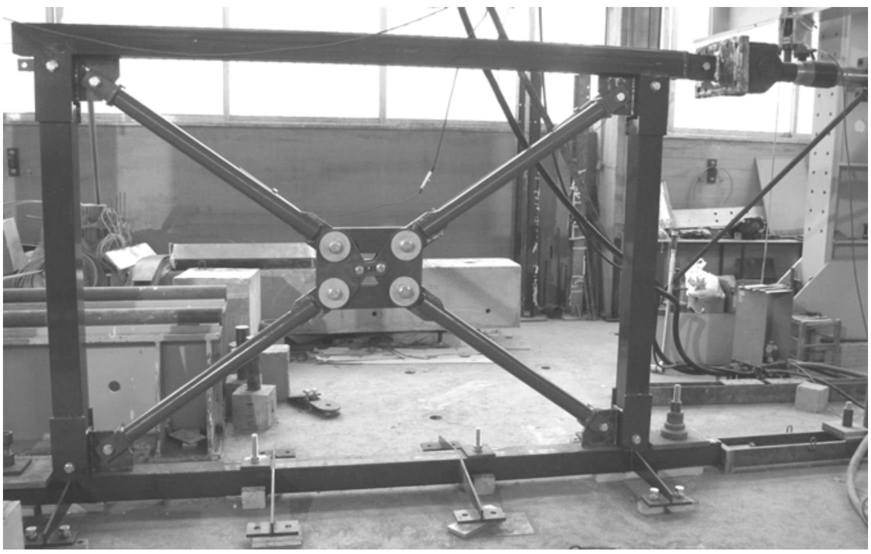


Fig. 4 Specimen during installation phase

Tests were performed at the Laboratory of the Concrete and Masonry Structures at the Aristotle University of Thessaloniki. For this purpose the reaction frame that is shown in Fig. 3 and a MTS double acting actuator of ±250kN capacity were used. The loading history was consisted of repeated imposed cycles for a displacement level of 50 mm. Deflections and deformations of the specimen were measured by externally-mounted displacement sensors (LVDTs). The arrangement of the LVDTs mounted on a typical specimen and the corresponding nomenclature are shown in Fig. 3. The LVDT measurements and the recordings of the actuator's load-shell were used to draw the load vs. displacement shown in the remainder of the paper.

5. Test results

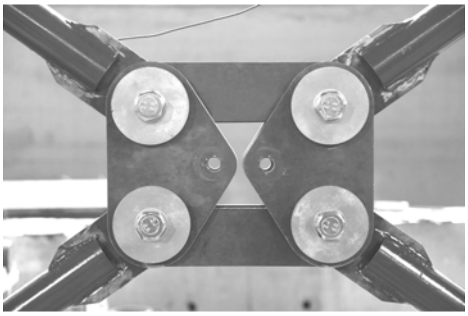
Nine tests were performed. In three tests, a set of single flanges were used at the friction device. The pre-stressing forces were applied by tightening the four bolts at a rotation moment of 0.3, 0.5 and 0.7kNm. Three more tests were also performed with the same pre-stressing forces while a set of double flanges was used. In three other tests the pre-stressing force was applied at a rotation moment 0.7kNm and two different link elements were used. The friction device that was used performed well during test. The resistance of the device during the imposed displacement cycles was kept almost constant without observing any descending contribution due to fatigue effects among the different tests. For each test a code name was given. The name begins with BF that is the initial letters of the phrase Braced Frame. The third letter is alternatively D or S noting that a set of Double or Single set of flanges was used respectively. After that a number follows 3, 5 or 7 noting that the torque moment that was applied at the bolts of the internal mechanism was 0.3kNm, 0.5kNm or 0.7kNm respectively. Finally the letter L was added in two tests denoting that a Link element was used to the proposed device. In Fig. 5 the device during and after the operation is shown together with the nomenclature of the specimens.

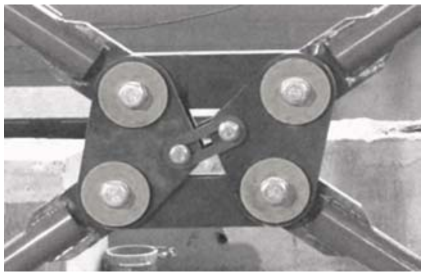
The recorded load – displacement hysteresis loops are given in Figs. 6 to 9. The proposed device provides almost constant strength. This is observed into the hysteresis loops which have almost constant (horizontal) upper and lower limits. In Figs. 7 right and 8 right where the tightening moments were 0.5 and 0.7 kNm respectively and double flanges are used the upper and lower envelope curves have a slightly inclined branch. This is attributed to the influence of the high friction force to the response of the diagonal braces. Due to high pre-stressing force these diagonal braces bend, resulting to an increase of the resistive force. After the point of maximum displacement when the load is zero a slip is represented in the recorded hysteresis loops. This is attributed to the lash between the parts of the surrounding frame at the rotational hinges of the beam column joints.

A detailed description of the recorded response of the proposed devices is listed as follows:.

Stage 1: The first ascending branch of the diagrams is defined from zero point to the point where the static friction moment was overpassed.

Stage 2: After the point that stage 1 ends, an almost horizontal branch appears denoting that the contribution of friction device is constant. During some tests where higher torque moments were applied, at the pre-stressed bolts, this branch has an increased inclination. As explained earlier this is attributed to the bend of the diagonal braces and thus to a higher contribution to the resisted force close to the end of this stage.





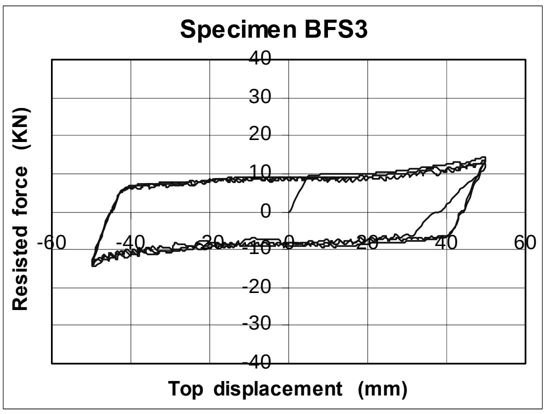
BFS3,5,7
2 flanges
at each corner

BFS7L
2 flanges
at each corner

BFD3,5,7
4 flanges
at each corner

BFD7L
4 flanges
at each corner

Fig. 5 Left: friction device without link element. Right: friction device with link element that is activated. Low: nomenclature of the tested mechanisms



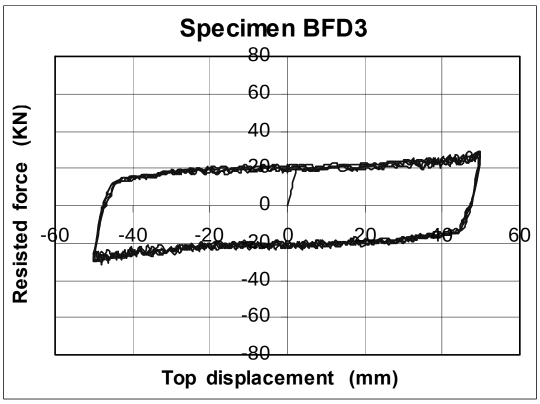


Fig. 6 Hysteresis loops for specimens BFS3 and BFD3 during tests

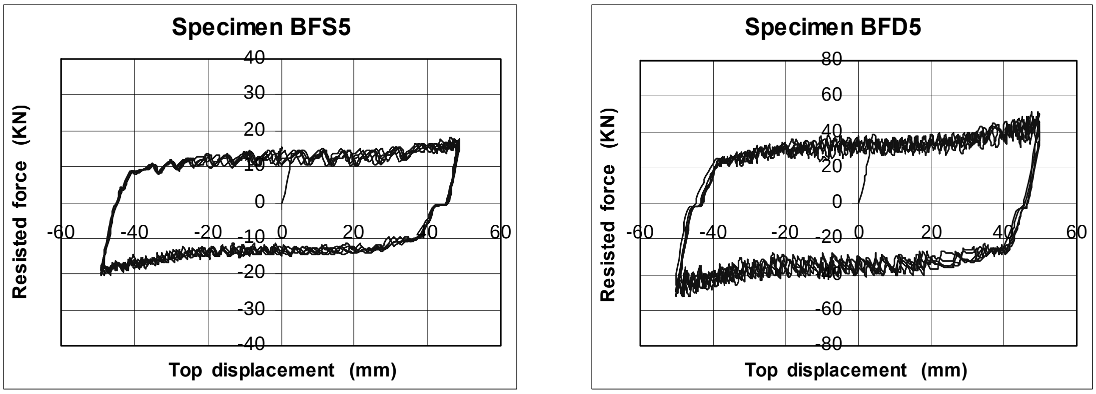


Fig. 7 Hysteresis loops for specimens BFS5 and BFD5 during tests

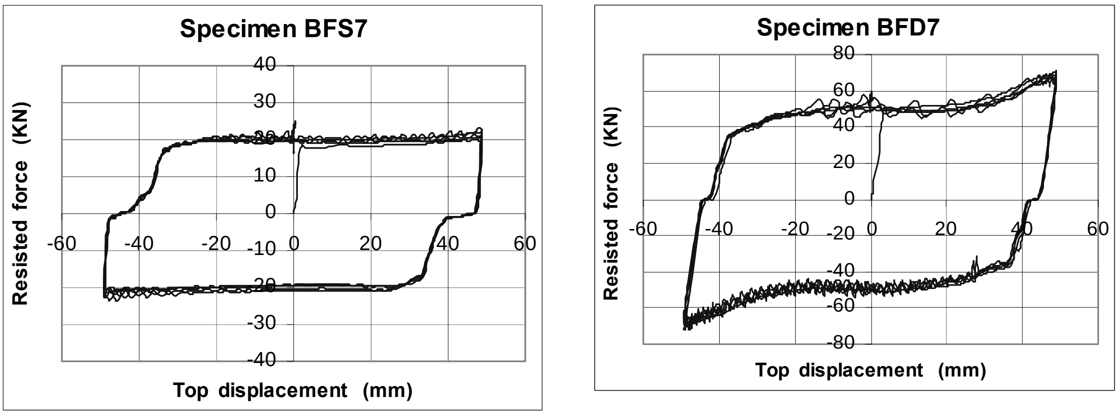


Fig. 8 Hysteresis loops for specimens BFS7 and BFD7 during tests

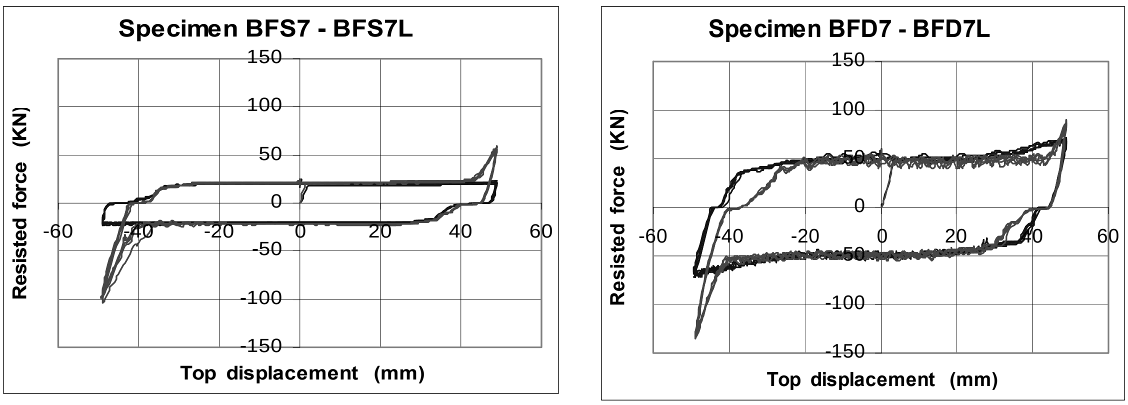


Fig. 9 Comparative diagrams of specimens BFS7 (left) and BFD7 (right) without and with link elements during tests

Stage 3: The link element was used in specimens that are referred on diagrams BFS7L and BFD7L. When the link element was locked the strength of the specimen was significantly increased. This increase in strength has high inclination and thus is developed for a small increase of the imposed displacement. The strength increase during the two half cycles of loading is not the same. This is attributed to small construction and response differences of the specimen in two directions.

Stage 4: After maximum strength the imposed displacement changes direction. The resistance of the specimen is reduced to zero at the end of this stage.

Stage 5: At the beginning of this stage a slip is observed in most specimens. This is attributed to the existence of initial loosening at the free rotational hinges of the specimen. This type of slip was also observed during the beginning of stage 1 but necessary corrections were applied. During this stage the resisted strength is increased again until the overpass of static friction moment.

Stage 6: In this stage the response of the specimen is similar with its response during stage 2 and an almost constant strength is represented.

After that stage 6 the device operates in second half cycle of displacement like in stages 2 to 6 until the cycle is completed. The quantities of the energy that was absorbed during tests are shown in Fig. 10. The increase of the absorbed energy was found to be analogous to the tighten moment of the bolts and to the existence of single or double friction flanges. By regulating the tighten moment and using single or double flanges is possible to assign the appropriate resisting capacity to the proposed device.

6. Numerical modeling of the specimens and case study

For the modelling of the arrangement, the SAP2000 software is utilised. The non-elastic PushOver process is carried out for large displacements, where in every step of the analysis both the new deformed geometry of the arrangement and the carrier is taken into account. Therefore the linearization of the diagonal rod and the securing of the displacements are automatically recognised by the software. For the simulation of the device, NLINK element which is provided by the software is used. The element PLASTIC utilised for the modelling of the rotational friction links. The non-linear behaviour of the element with respect to rotation and the non-linear properties are described in Fig. 11. The slip paths in the oblong holes simulated with the use of NLINK elements GAP and HOOK.

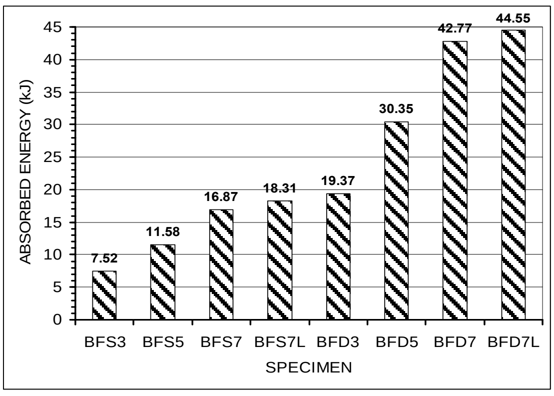


Fig. 10 Absorbed energy by the tested specimens

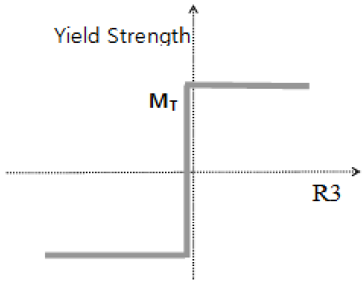


Fig. 11 Modeling of rotational friction links. Moment-rotation diagram at the points of the friction flanges

The structural steel elements that compose the specimen with the appropriate releases and rotational plastic hinges are simulated. In Fig. 12 the analytically simulated hysteresis loops of specimen BFD7L are shown in comparison to the recorded hysteresis loops during the test of the same specimen. The tested specimens and the proposed friction device was constructed under 1:2 scale. The increase of strength is analogous to the torque moments that are applied at the bolts of the friction mechanism. Three values of the torque moments that were applied at the bolts are 0.3, 0.5 and 0.7kNm. The resisting moment for the various levels of torque moments applied at the bolds are computed through reverse calculation by the use of the recorded load during the experiments. The cases that should be considered are three with single flanges for three levels of applied torque moment at the bolts and three with double flanges and the same torque moments at the bolts. Two more cases with double flanges, torque moment at the bolt 0.7kNm and addition of a link element at the friction device were also considered. As resistive shear, V_R that was recorded at the experiments, is considered the load at the hysteresis loops when the displacement passes from the zero point (Y axis value) at Figs. 6 to 9. The load torque moment at the flanges results from the aforementioned shear force divided by two (for the two vertical branches of the internal device) and multiplied by the half length of the branch (components I and II of Fig. 1).

$$M_{TR} = (L/2)*(V_R/2) = (0.1)*(V_R/2) \quad (1)$$

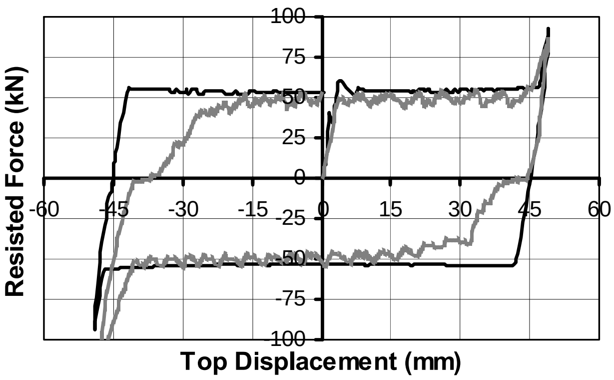


Fig. 12 Force – displacement hysteresis loop for the finite element model of specimen BFD7L (Scale 1:2) and comparative representation of the hysteresis loops of tested specimen (gray line represents specimen)

Table 1 Resisted shear forces and resisted torsion moments for the friction devices

SPECIMEN	LOAD V_R				V_{R0} calculated at δ=0	M_{TR}
	V_{R0} at δ=0	$\lvert V_{Rmax}\rvert$ at $\lvert\delta_{max}\rvert$	Coefficient		V_{max} calculated Single $1.60\times V_{R0,calc}$ Double $1.44\times V_{R0,calc}$	
	kN			Medium Value	kN	kNm
BFS3	8.65	14.49	$V_{R0}/0.3=29$	29	0.3×29=8.7 1.60×8.7=13.9	0.43
BFS5	13.05	20.40	$V_{R0}/0.5=26$		0.5×29=14.7 1.60×14.7=23.5	0.65
BFS7	20.10	22.25	$V_{R0}/0.7=29$		0.7×29=20.3 1.60×20.3=32.5	1.01
BFS7L	21.10	With link 94.20	$V_{R0}/0.7=30$		0.7×29=20.3 ------	1.06
BFD3	20.75	29.75	$V_{R0}/0.3=69$	70	0.3×70=21.0 1.44×21.0=30.2	1.04
BFD5	33.90	51.00	$V_{R0}/0.5=68$		0.5×70=35.0 1.44×35.0=50.4	1.70
BFD7	49.90	70.49	$V_{R0}/0.7=71$		0.7×70=49.0 1.44×49.0=70.6	2.50
BFD7L	49.55	With link 133.30	$V_{R0}/0.7=71$		0.7×70=49.0 ------	2.48

V_{R0}: Shear strength during the pass from the beginning of the axes

V_{Rmax}: Shear strength that corresponds at maximum displacement

M_{TR}: Torsion moment given by Eq. 1 for V_{R0} for use in analytical predictions

The resisted torque moments M_{TR}, at the friction rotational hinges of the device are given in Table 1. The coefficients that relate the torque moment with the resisted shear force, for the tested mechanism are 29 for the single set of flanges and 70 for the double set of flanges. By the use of these coefficients results good coincidence between recorded and calculated shear forces. These values are used as input data to a finite element model that simulates the specimen. This model for specimen BFD7L, is subjected to imposed cyclic displacement of 50mm. The resulted hysteresis loops are presented at the comparative diagrams on Fig. 12. The recorded hysteresis loops are satisfactorily approached by the proposed calculations in Table 1 and by the analytical model.

A five storey, five bay, real scale reinforced concrete frame (shown in Figs. 13A, B) is also analytically simulated. The analytical model contains plastic hinges at the ends of beams and columns. These plastic hinges appropriately simulate the inelastic properties of the ends of each structural element. The frame is analyzed without and with the proposed device, in real scale, that is embodied in the aforementioned RC frame. It is not necessary to enter the proposed device at the same bay along the height of the building. For this reason the friction device is embodied in different spans into the plain frame. Figs. 13C, D show the push over curves that result before and after the use of the proposed mechanism. The friction device represents specimen BFD7. For the properties of the exact device that will result from the specimen, the structural modeling under

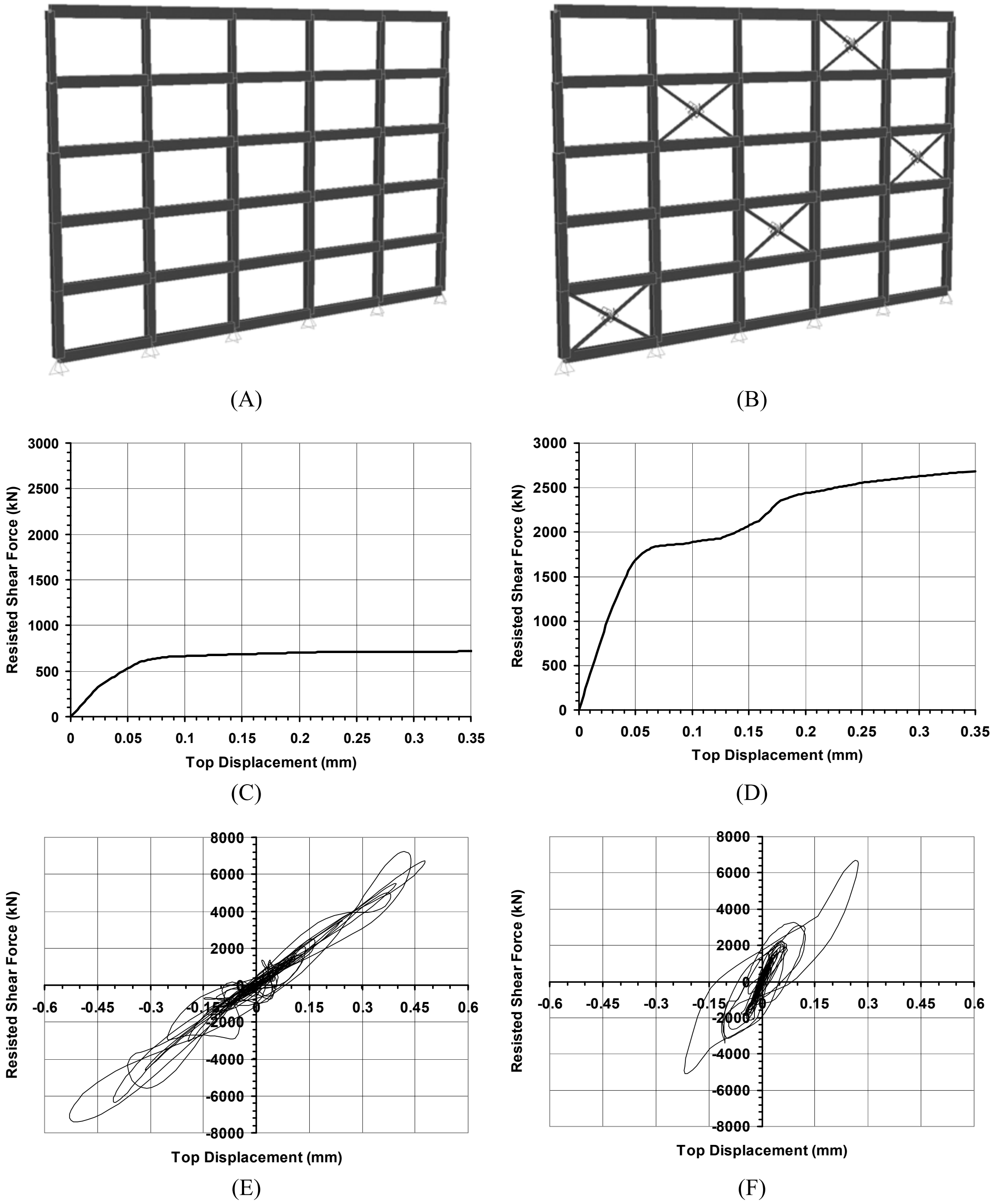


Fig. 13 (A) Bare five storey frame. (B) Five storey frame with the proposed mechanism embodied. (C), (D) Push over curves for the aforementioned frames respectively. (E), (F) Hysteresis loops of the aforementioned frames for Thessaloniki 1978, M6.5 earthquake

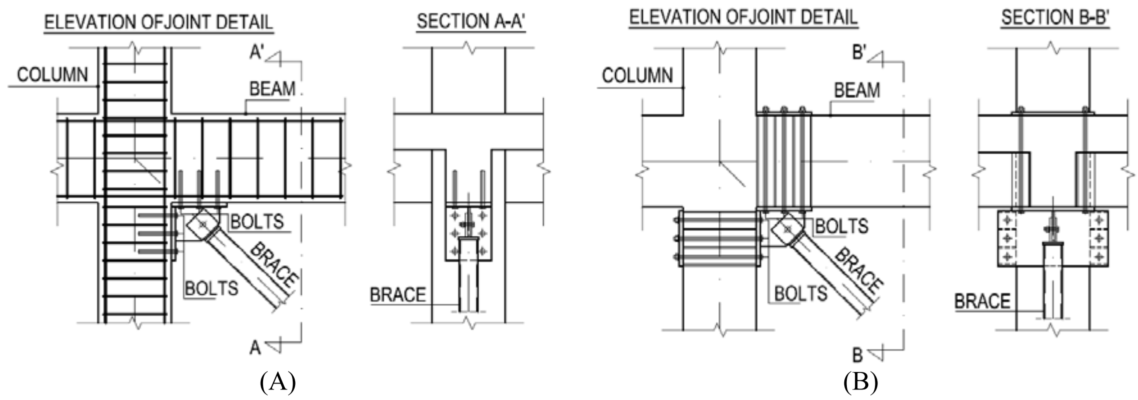


Fig. 14 Details of the structural elements framing into a joint. Two alternative schemes: (A) use of anchored bolts inside the concrete, (B) use of bolts and plates at the two faces of the structural elements

scale should be used that is described by Sabnis *et al*. (1983). The strength of the friction device was the strength of the specimen multiplied by the square of scale value of the friction device ($\times 2^2$).

The deformation of the friction device was taken equal to the deformation of the specimen multiplied by the scale value of the friction device. In order to achieve of the above described strengths of the exact friction device the rotational moments of Table 1, that should be applied at the bolds should be multiplied by the cube of the construction scale of the specimen ($\times 2^3$). Figs. 13E, F show the hysteresis loops that resulted from the aforementioned frames when are subjected to Thessaloniki 1978, M6.5 earthquake. The response of the frame, where the proposed mechanism was used, is significantly superior to the response of the frame with no mechanism. Details of a joint where structural elements are framing are shown in Fig. 14. Previous publications in the field emphasizing the need for the present research are given by Papadopoulos and Athanatopoulou (2002), and Papadopoulos and Mitsopoulou (2008).

7. Conclusions

A friction device with a novel type link element for the increase of the shear capacity of Reinforced Concrete or Steel multi-storey frames, at a desired level, is presented. The device has the capacity to lock at a predefined level of displacement, resulting thus to the provision of supplemental strength at the strengthened frames. This predefined level of displacement is related with the gap that is provided at the steel link element. Also the inelastic displacements may be limited by the use of this device. The three different stages of operation were experimentally and analytically validated. These three stages are

i) elastic resistance without rotation at frictional hinges,

ii) rotation at frictional hinges by providing additional constant resistance and energy dissipation,

iii) lock of the device, limitations of the displacements and strength increase.

These stages define the main characteristics of the device that are the increase of stiffness, the increase of energy dissipation during imposed cyclic loads and the additional protection during strong earthquakes where high inelastic deformations are expected. A very important advantage of the device is the easy predefinition of its properties in order to satisfy design criteria. The properties of the device, at the elastic stage, depend on the pre-stressing forces that are applied at the bolts at the frictional hinges, the material properties of the steel flanges and the layers of the flanges that are used (single, double etc.). Besides the aforementioned lock property, exists the possibility to use many layers of frictional flanges (in combination with the link element) to multiply the provided resistance and dissipation capacity. The experimentally measured response of the specimens was approached by analytical calculations and models. Also an application was presented showing that the proposed device can effectively improve the strength and the response of R/C frames against seismic actions.

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