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A NEW SEISMIC ENERGY ABSORPTION DEVICE THROUGH SIMULTANEOUSLY YIELD AND FRICTION USED FOR THE PROTECTION OF STRUCTURES

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ABSTRACT

Passive energy dissipation systems do not require external power to generate system control forces and hence, are easy and cheap to implement in a structure (existing or new). The new seismic energy absorption device, which is presented in this paper, is an improvement of the device CAR, proposed by Papadopoulos et al (2008) and it is incorporated at the ends of the steel diagonal bars. The improved device, through replaced the traverse elastoplastic regulation bolts with superimposed steel blades, aims at avoiding material fatigues of the bolt because of the repeated load cycles. Also it has many advantages. First of all, it limits the maximum axial forces developed in the steel diagonal bars of the structure, with the appropriate choice of dimensions and characteristics of the superimposed steel blades. Also, allows additional horizontal relative floor displacements of the structure without increasing the axial load of the steel diagonal bars, which means increase of the absorbed seismic energy. The main advantage of the proposed new device is that it can function reliably under large cycles of dynamic load, where large horizontal relative floor displacements develop. At the same time, when the horizontal relative floor displacement reaches a characteristic value, then the new device locks, so that the buckling of the compressed diagonal bars is decisively removed, so introduces second degree of protection of the structure in the case of very strong earthquakes. So this improvement is capable of producing higher axial forces and deformations, before the collapse. In order to investigate the suitability of the new proposed device CAR1 described in the present paper, nonlinear analyses have been carried out using, on one hand, a static pushover procedure with lateral floor monotonic incremental static forces with a triangular distribution in elevation and, on the other hand, nonlinear response history analysis with suitable seismic artificial accelerograms. Two different structures of reinforced concrete are used, of which the first is a one storey planar structure with five frames and the second is a three storey planar structure. Also each structure is being analyzed using the pushover analysis and time history analysis, as regards three different cases, the initial pure r/c frame without strengthening, the simple strengthening frame and the strengthening frame with the new proposed device CAR1.

INTRODUCTION

The safety of construction (existing or new) is one of the major priorities of engineering globally, because structures often subject to large and often devastating, for their viability, loadings. The law of conservation of energy imposes the restriction that the energy must either be absorbed and/or dissipated by the structure. Most structures have an inherent damping in them which results in some of

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this energy being dissipated, but a large amount of energy is absorbed by the structure, undergoing several deformations and maybe even collapse. So, great interest is in the study of the innovations of the design and materials of construction that minimize the probability of failure of the structure in any charging. Therefore, many efforts have been made to create devices that will absorb the majority of the seismic energy but will not belong to the supporting structure of the construction. The main advantages of these, is the easy replacement or repair. These devices belong to the passive energy dissipation systems, do not require external power to generate system control forces and hence, are easy and cheap to implement in a structure.

Passive energy dissipation devices such as visco-elastic dampers, metallic dampers and friction dampers have widely been used to reduce the dynamic response of civil engineering structures subjected to seismic loads. Their effectiveness for seismic design of building structures is attributed to minimizing structural damages by absorbing the structural vibratory energy and by dissipating it through their inherent hysteresis behavior (Soong et al. 1997).

Among these dampers, friction dampers with various designs have been developed and applied for the seismic protection of building structures since their hysteretic behaviors could be kept stable for cyclic loads and desirable slip loads are easily abtained by regulating normal forces acting perpendicularly to a friction surface, in addition to their simple energy dissipation mechanism and easy manufacturing, installation and maintenance (Pall and Marsh, 1982; Fitzgerald et al., 1989; Constantinou et al. 1990; Grigorian et al 1993, Papadopoulos 2012).

THE PROPOSED DEVICE

A new seismic energy absorption device is presented in this paper. The device is an improvement of the device CAR proposed by Papadopoulos et al (2008). Both devices have the advantage to (i) provide additional stiffness as well as (ii) absorption of seismic energy, (iii) provision of control of the axial forces that are developed at the diagonal steel rods and last but not least the ability to retain the plastic displacements to a desired level.

The parts of this improved device are one exterior tube, one interior steel shaft and five groups of superimposed steel blades, as shown in Figure 1. The improved device, after replacing the traverse elastoplastic regulation bolts with superimposed steel blades, aims at avoiding material fatigues of the bolt because of the repeated load cycles. So this improvement is capable of producing higher axial forces and deformations, before the collapse.

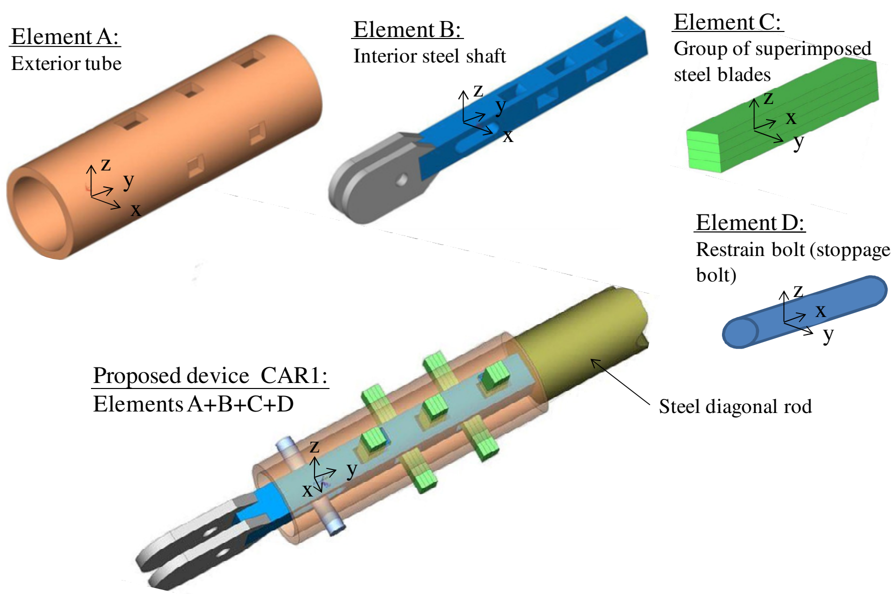

Figure 1. The parts of the CAR1 device

The relevant movement of elements A and B is carried out by an elastoplastic bending deformation of the superimposed steel blades that connect crosswise elements A and B. The number and the dimensions of superimposed steel blades as well as their elastoplastic characteristics define the principle of elastoplastic behaviour of the diagonal bars on an axial load. There is also a provision for a Restrain bolt (stoppage bolt). This bolt is made of high yield Steel, and can slide inactively through an appropriately selected oval hole at element A. As a result, the activation of this bolt is carried out at a "second time" and it allows the desired plastic deformations of the superimposed steel blades to take place. The activation of the stoppage bolt allows the transfer of an additional axial load from elements A to element B of the device. An appropriate configuration / geometry in the area of the stoppage bolt (oval hole) eliminates any additional compression forces on the diagonal elements and allows only tensional forces to be developed.

The proposed device can be used on new or existing structures, and can easily be adapted to the particular demands of their various functional or relevant architectural requirements. It can be installed in a variety of ways which include using them in single diagonal braces (one or two devices), in cruciate diagonal steel rods (two or four devices) and other types of diagonal steel rods, as shown in Figure 2.

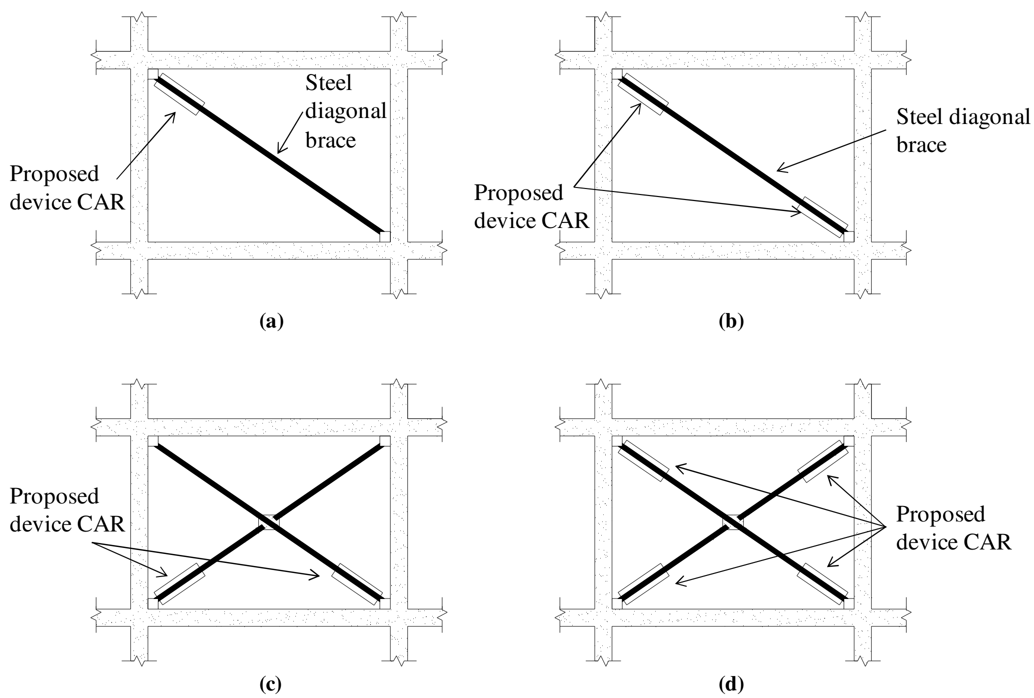

Figure 2. (a) One device CAR1 in single diagonal brace, (b) Two device CAR1 in single diagonal brace, (c) Two device CAR1 in cruciate diagonal steel rods, (d) Four device CAR1 in cruciate diagonal steel rods

Operational stages of the proposed device CAR1:

The operation of absorbing energy devices which have the ability to restrain displacement, as has been studied by previous researchers (Roik et al., 1988; FitzGerald et al., 1989; Lukkunaprasit et al., 2004; Papadopoulos and Mitsopoulou, 2008; Ramirez and Tirca 2012), is based on the following four discrete stages (Figure 3):

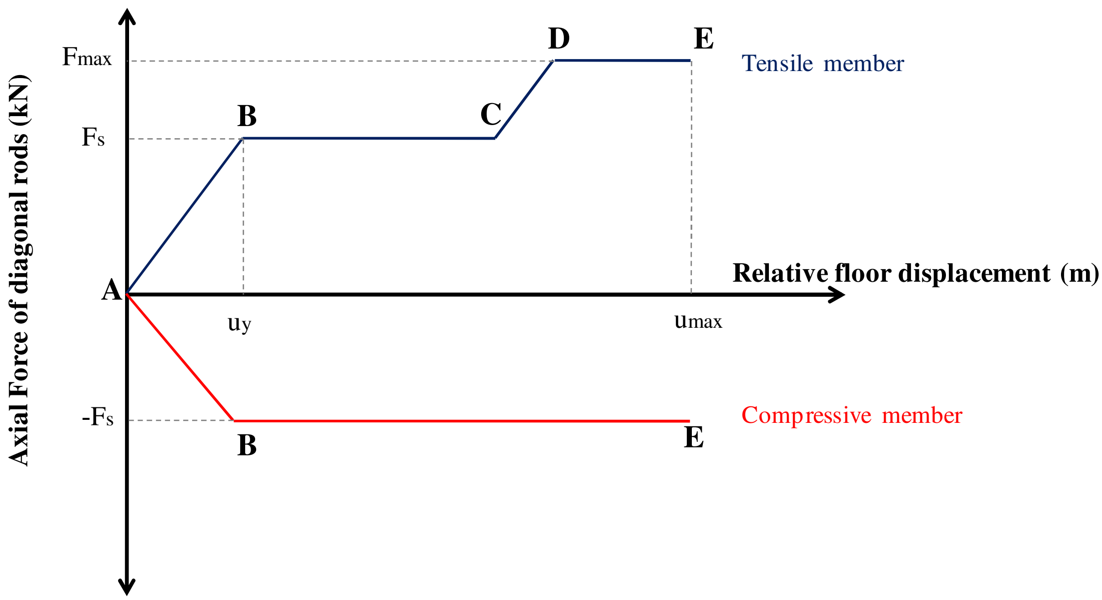

Figure 3. Non-linear multi-linear behaviour of the diagonal steel robs for tension and compression stress

Stage 1: The device is off (A-B). The bending of the superimposed steel blades is not activated and the diagonal steel rods operating in the elastic area until reaching the predetermined load Fs.

Stage 2: The device is on (B-C). The device operates as a mechanism. Activated bending and friction of the superimposed steel blades. The diagonal steel rods remain in the elastic area with a constant value equal to the maximum power of the previous stage, Fs.

Stage 3: The device is locked (C-D). Therefore, the tensile diagonal bar is fully activated. More specifically, the locking of the device causes an increase of the tensile axial force of the diagonal steel rods and an additional lateral strength of the frame is presented. At the same time, the compressive diagonal steel rods have the capacity of further "axial movement", which prevents the development of any additional axial forces on the rods. So, the compressive axial force has a constant value after the locking of the device.

Stage 4: The strengthening frame is protected against collapse (D-E). In the case of greater horizontal relative floor displacements, and until the strengthening frame reaches "the failure relative floor displacement", the tensile diagonal steel rods may yield due to tension. At the same time, the compressive diagonal steel rods continue to undergo compression in a controlled way, without an increase of its compressive axial force value; therefore, the buckling of the compressive bar is avoided.

Modeling of the proposed device CAR1:

The proposed device CAR1 was modelled and analyzed in program SAP 2000 ver. 15.0. The connection of the rods to the R/C frame is simulated by a macro model of two parallel N-Links elements that the program provides. The N-Links element plastic was used for the superimposed steel blades and the N-Links element Hook for the restrain bolt. Both elements have non-linear qualities.

DESCRIPTION OF THE STRUCTURES

As the strengthening building with X-diagonal steel rods is the most common type of multistory buildings, two different structures of reinforced concrete are used, the first is a one storey planar structure with five frames and the second is a three storey planar structure. Also each structure is being analyzed using three different cases, the initial pure r/c frame without strengthening, the strengthening frame only with diagonal steel rods and the new proposed device CAR1.

One storey planar structure:

A one storey planar structure with five panels (Figure 4) was chosen to be studied. Each panel has a height h=3m and length l=5m. The horizontal elements are beams with dimensions in plan 25x50cm and the vertical are columns with dimensions in plan 35x35cm. This model is named BM1. The seismic efficiency of the proposed device in the BM1 was evaluated through two different design schemes DS1 (Figure 5) and DS1-CAR1 (Figure 6). The structures are the same as the BM1 by strengthening the first panel with diagonal steel rods (SASE). Two variations were studied in relation to the way of fixing the SASEs: (i) Classic fixed connection where the activation of the Special Steel Anti-seismic Elements is direct with equal displacements of the nodes of the R/C structure and the Steel diagonals (DS1 model) and (ii) Insertion of the suggested CAR1 device on the connection of the SASEs with R/C elements. The diagonal steel rods are hollow circular cross sections with diameter equal to 11.4cm and thickness 0.36cm.

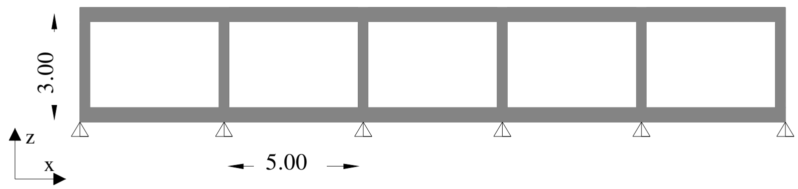

Figure 4. The one storey planar structural system BM1

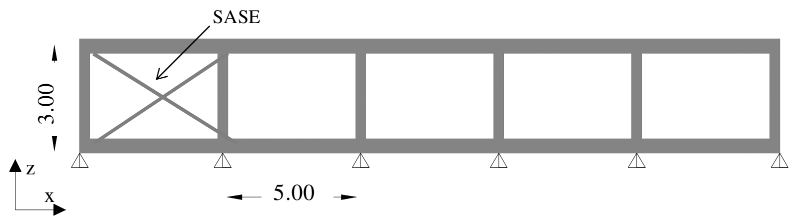

Figure 5. The one storey planar structural system DS1

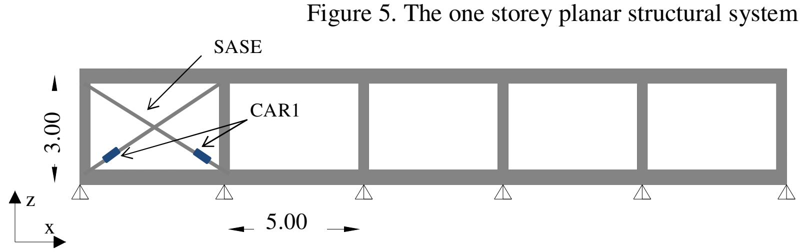

Figure 6. The one storey planar structural system DS1-CAR1

Three storey planar structure:

A three storey planar structure with five panels (Figure 7) was chosen to be studied. Each panel has a height h=3m and length l=5m. The horizontal elements are beams with dimensions in plan 25x50cm in 1^{st} and 2^{nd} floor, 25/40 in 3^{rd} floor and the vertical are columns with dimensions in plan 45x45cm in1^{st} and 2^{nd} floor and 40x40in 3^{rd} floor. This model is named BM2. The seismic efficiency of the proposed device in the BM2 was evaluated through two different design schemes DS2 (Figure 8) and DS2-CAR1 (Figure 9). The structures are the same as the BM2 by strengthening one panel of each floor with diagonal steel rods (SASE). Two variations were studied in relation to the way of fixing the SASEs: (i) Classic fixed connection where the activation of the Special Steel Anti-seismic Elements is direct with equal displacements of the nodes of the R/C structure and the Steel diagonals (DS2 model) and (ii) Insertion of the suggested CAR1 device on the connection of the SASEs with R/C elements. The diagonal steel rods are hollow circular cross sections with diameter equal to 11.4cm and thickness

0.40cm in the 1st floor, diameter 10.20cm and thickness 0.36cm in the 2nd floor and diameter 89cm and thickness 0.32cm in the 3rd floor.

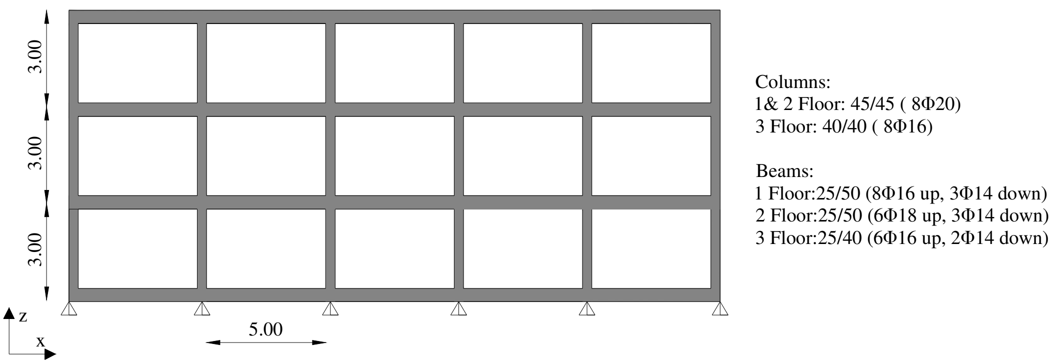

Figure 7. The three storey planar structural system BM2

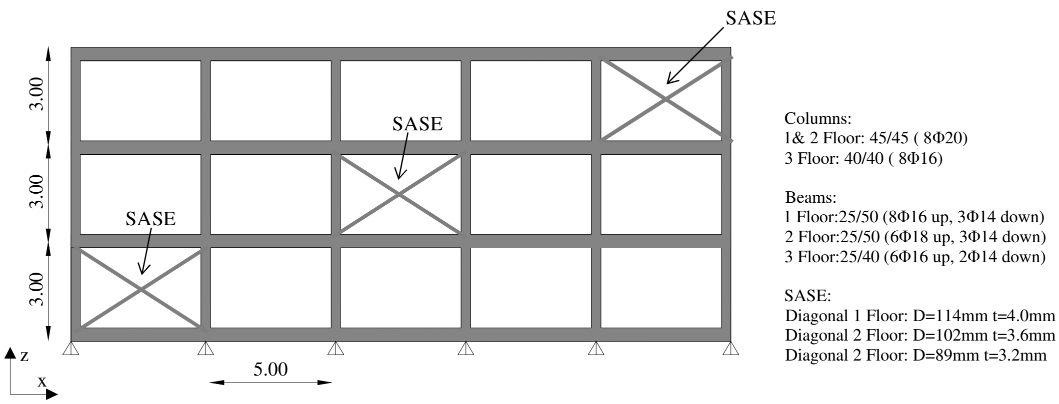

Figure 8. (a) Direction x of the two storey structural system DS2, (b) Direction y of the two storey structural system DS2

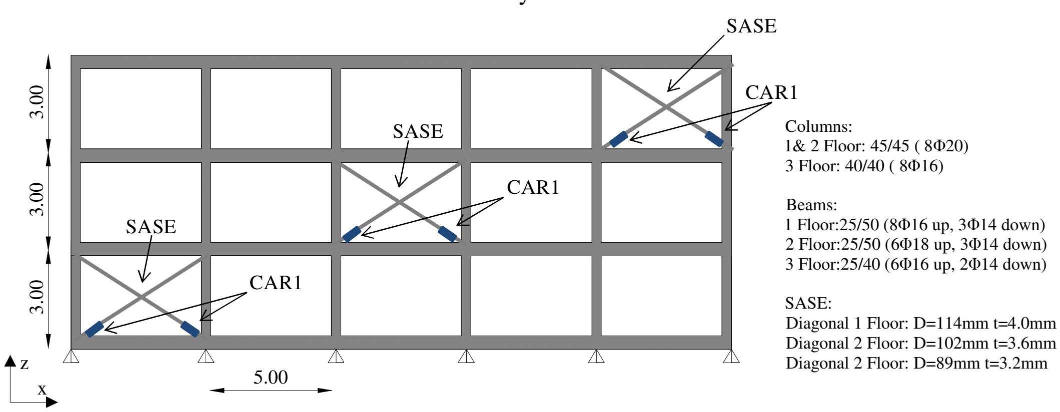

Figure 9. (a) Direction x of the two storey structural system DS2-CAR1, (b) Direction y of the two storey structural system DS2-CAR1

RESULTS OF ANALYSES

One storey planar structure:

The maximum base shear of the frame is 540 kN and the ultimate horizontal floor relative displacement is 80 mm, as produced by the static pushover analysis in figure 10. Using the pushover curve, the new steel device is easily calculated. With regard to the pushover curves $V_o - u_{top}$, i.e. the "base shear and horizontal relative floor displacements", shown in Figure(10), the proposed steel device has increased the lateral stiffness of the frame by up to 50%, the yielding base shear by up to 1.42 times and the total lateral strength of the frame by up to 5 times, without affecting the total available ductility of the frame.

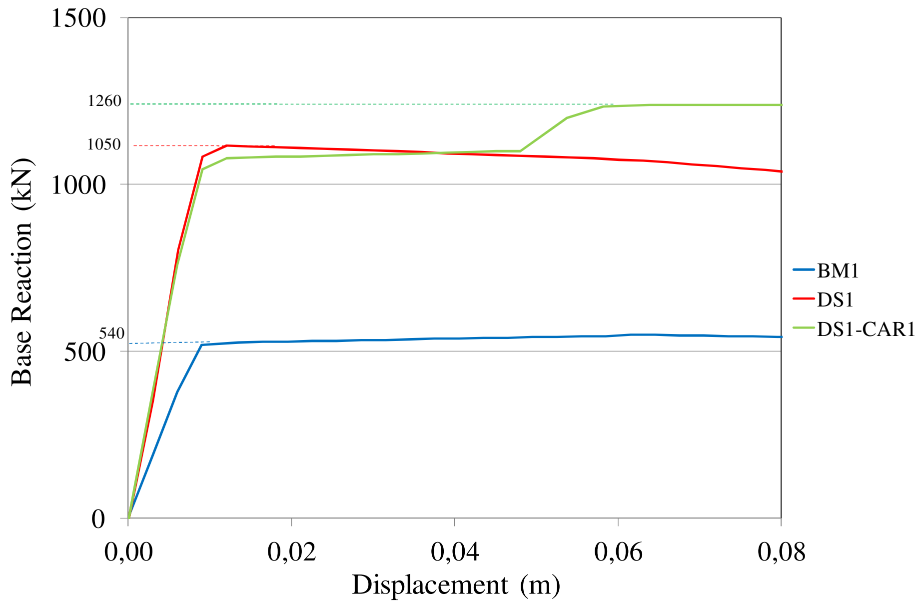

Figure 10. Push over curves

The numerical model of the planar single-storey r/c frame strengthened with simple diagonal steel bars without use the proposed device is examined for reasons of comparison. Initially, in order to calculate the simple diagonal steel bars, static pushover analysis has been applied. The results of the analysis have shown that, on the one hand, the diagonal steel bars contribute with additional lateral strength on the frame, but on the other hand, a premature failure of the diagonal bars occurs, due to buckling/compression or tension. This failure is a major disadvantage. In fact, figure 11(red line) shows that the strength of the compressive bar presents a premature and sudden drop, due to the buckling phenomenon. The proposed steel device CAR1 fully addresses the issue of the premature failure of the compressive bar due to buckling, since the former does not permit the buckling of the diagonal steel bars. When the device locks, then (a) the tensile diagonal steel bar is fully activated and (b) the compressive diagonal steel bar does not go into buckling for the additional horizontal relative floor displacements, figure 11 (green line). The two advantages mentioned above provide the frame with the necessary lateral strength against seismic actions.

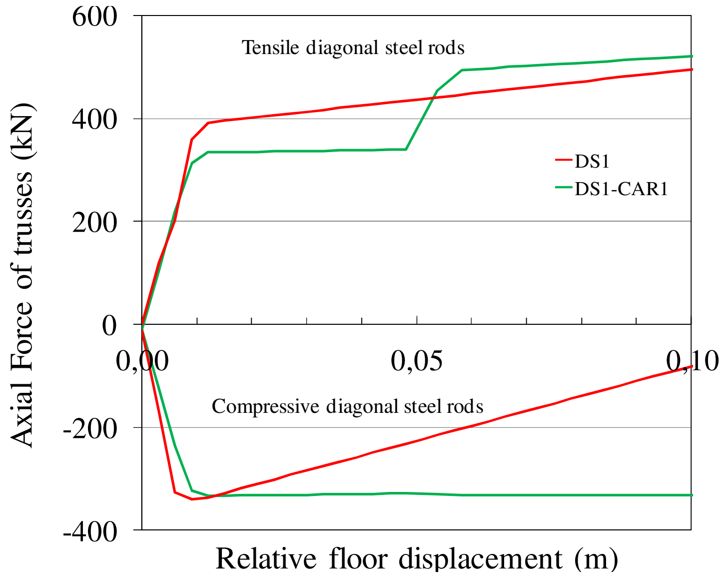

Figure 11. Axial forces of the diagonals steel rods of DS1and DS1-CAR1

In figure 12 the quasistatic cycling load versus time for wich the time history analyses were performed is presented. Also in Figure 13 is presented the variation of the axial forces of the diagonals versus the horizontal displacement of the top beam. It is observed that the SASEs operate under safe conditions.

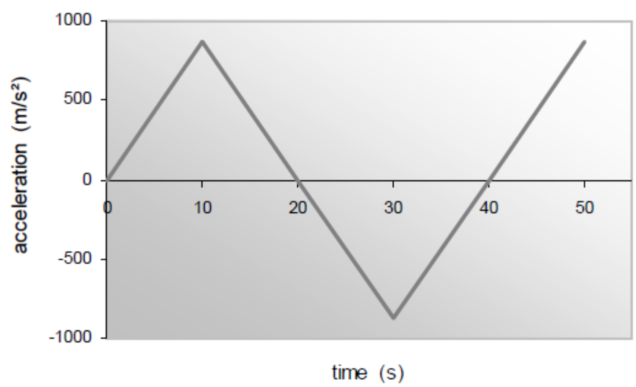

Figure 12. Diagram of load and time for time history analysis

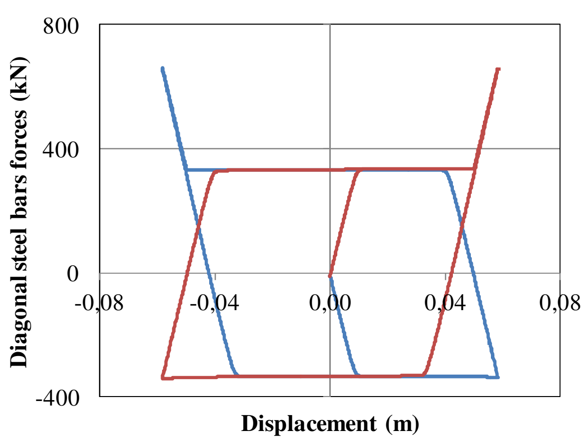

Figure 13. Axial forces of the diagonals steel rods of DS1-CAR1

As has been shown by the results of the previous non-linear analyses, the new proposed steel device helps to prevent the buckling of the compressive diagonal steel bar, to develop friction in order to create hysteretic loops, and to provide additional lateral strength due to the full activation of the tensile diagonal steel bar and the unobstructed operation of the proposed device under large load cycles

<u>Three storey planar structure:</u>

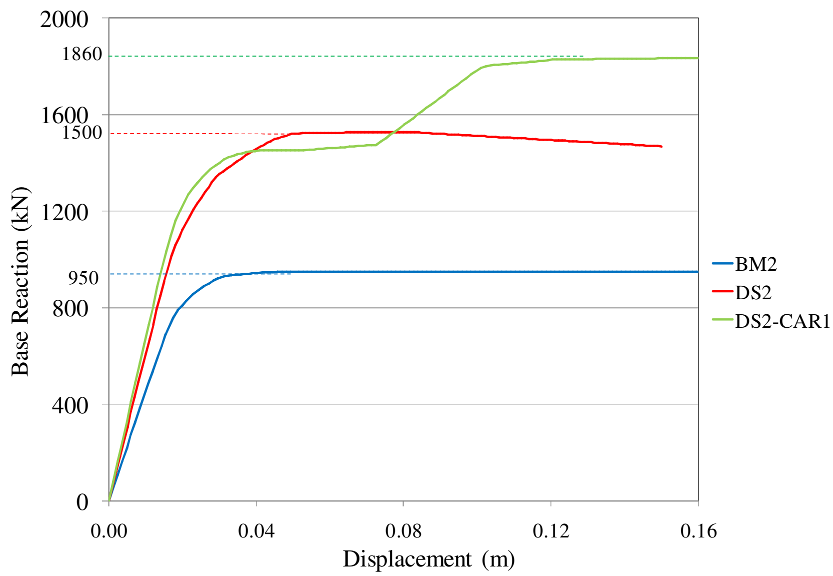

Figure 14. Push over curves of three storey planar structure

Figure 15(red line) shows that the strength of the compressive bar of the 1rst floor presents a premature and sudden drop, due to the buckling phenomenon. The proposed steel device CAR1 fully addresses the issue of the premature failure of the compressive bar due to buckling, since the former does not permit the buckling of the diagonal steel bars. When the device locks, then (a) the tensile diagonal steel bar is fully activated and (b) the compressive diagonal steel bar does not go into buckling for the additional horizontal relative floor displacements, figure 15 (green line).

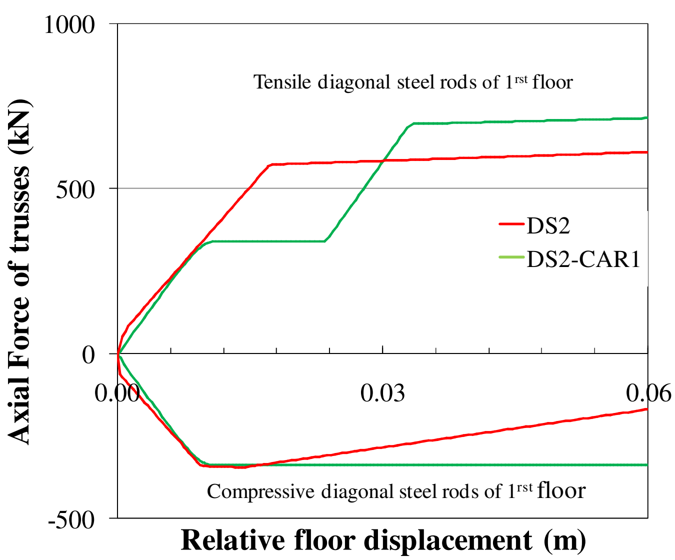

Figure 15. Axial forces of the diagonals steel rods of DS2and DS2-CAR1

All models of the three floor planar structure, i.e. the benchmark BM_2 and the alternative schemes DS_2 and DS_2-CAR1, were analyzed for several different artificial accelerograms that were compatible to ground type B-dependent Eurocode 8 elastic spectra. The selection of the accelerograms, was based on the provisions of Eurocode 8 Part 1 (2005). The direct integration, known as β-Newmark method, was used. The mass and stiffness proportional damping was chosen and critical damping ratios equal to 5% and 4% were considered for the first and the second period of the analyzed bridge systems correspondingly. In figure 16 is presented the variation of the axial forces of the diagonals versus the horizontal displacement of the top beam. It is observed that the SASEs operate under safe conditions.

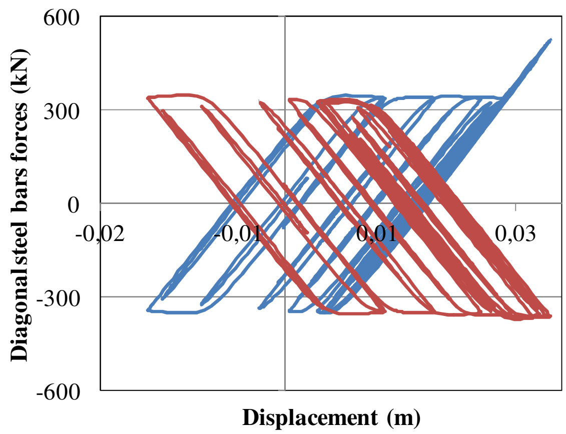

Figure 16. Axial forces of the diagonals steel rods of DS2-CAR1

CONCLUSIONS

The new device, which is presented in this paper, has the advantage to (i) provide additional stiffness as well as (ii) absorption of seismic energy, (iii) provision of control of the axial forces that are developed at the diagonal steel rods and last but not least the ability to retain the plastic displacements to a desired level.

More specifically, regarding to the locking capacity of the proposed device, the following properties are present. First of all, it limits the maximum axial forces developed in the steel diagonal bars of the structure, with the appropriate choice of dimensions and characteristics of the superimposed steel blades. Also, allows additional horizontal relative floor displacements of the structure without increasing the axial load of the steel diagonal bars, which means increase of the absorbed seismic energy. The main advantage of the proposed new device is that it can function reliably under large cycles of dynamic load, where large horizontal relative floor displacements develop. At the same time, when the horizontal relative floor displacement reaches a characteristic value, then the new device locks, so that the buckling of the compressed diagonal bars is decisively removed, so introduces second degree of protection of the structure in the case of very strong earthquakes.

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