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EVALUATION OF AN INNOVATIVE PASSIVE MITIGATION DEVICE THROUGH EXPERIMENTAL AND NUMERICAL INVESTIGATION

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Abstract. *There is a great need to develop innovative devices for the absorption of dynamic-seismic loads. The present study focuses on the development of such a passive mitigation steel device. The evaluation of the proposed innovative device occurred through experimental and numerical investigations. In this study the passive mitigation device is referred as CAR1. It comprises of three distinguished parts; the external cylindrical ring, the internal prismatic holder and several superimposed blades that are responsible for the transfer of forces between the aforementioned 2 parts. CAR1 is utilized for strengthening either existing or new steel structures or existing R/C structures. By using CAR1, the beam–column frames can be easily and safely strengthened at many predefined levels according to the demands of the seismic loads imposed by international norms and codes. The mechanism of the energy absorption is developed on the superimposed blades through both yielding of steel as well as friction. The number and dimensions of the superimposed blades, their elastoplastic properties as well as the friction coefficient at their interface, define the equivalent nonlinear constitutive law of the proposed device. A device with prototype dimensions was fabricated and investigated both numerically and experimentally under cyclic loading conditions. The numerical analyses conducted utilizing the FE software ABAQUS. The experimental sequences occurred at the premises of Laboratory for Strength of Materials and Structures of Aristotle University of Thessaloniki. The investigated variables are the geometry of blades and the number of cycles of the loading sequence. The obtained results revealed the overall mechanical behavior of CAR1. It was proven that the innovative proposed steel device CAR1 is an alternative system for calibrating and mitigating the seismic loads developed to a structure during an earthquake.*

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1 INTRODUCTION

The presented study focuses on the braced frames protection. Balendra et al. [1, 2] proposed a new fuse element, with high stiffness and suitable ductility, as knee braced frames in order to prevent buckling. Franco et al [3] presented a new yielding damper based on plastic properties of the metals. In another study, Papadopoulos P. in 2012 proposed a new metal frictional device, the capacity of a restricted rotation around the horizontal axis perpendicular to the vertical frame plane, in order to increase the seismic capacity of multi-storey planar reinforced concrete (r/c) frames [4]. Another way to protect braced frames is by using buckling restrained braced frames, as it has the same load deformation behavior in both compression and tension and higher energy absorption capacity with easy adjustability of both stiffness and strength [5, 6]. In addition, many researchers have proposed the use of post tensioning technology, in braced frames or in moment resisting frames, for residual drift reduction. A post-tensioned (PT) technique, which applies high-strength steel tendons to compress different structural members together, has been demonstrated to be effective in eliminating residual deformations of structures in cyclic loading [7, 8, 9].

In this present paper, an innovative passive mitigation steel device, mentioned as CAR1, for seismic strengthening of existing and new buildings, which was recently developed at the Laboratory of Experimental Strength of Materials and Structures of Aristotle University of Thessaloniki, is studied experimentally. Its effectiveness has been numerically verified [10, 11, 12]. The aim of the present study is to numerically replicate the experimentally obtained results in order to create a reliable tool for the simulation of the hysteretic behavior of the device CAR1 so as to identify the key parameters controlling the response of the CAR1 device. The investigated variables are the geometry of the blades, the velocity and the number of the cycles of the loading sequence. The obtained results depicted the overall behaviour of CAR1 with respect to the absorbed seismic energy, and whether or not it will break during the cycle loading.

2 DESCRIPTION OF THE INNOVATIVE MITIGATION DEVICE

The innovative passive mitigation steel device has the codename CAR1 and belongs to the passive energy dissipation system, as it doesn't require external power to generate system control forces. The device has variable behaviour in different levels of displacement. It has been designed so that could be locked at preselected level of displacement, offering in this way an extra safety reserve against strong earthquake. This device proposed by Papadopoulos et al. [10], it consists of 4 main elements, as illustrated in Figure 1. The exterior tube, the interior shaft, five groups of superimposed blades and the restraint bolt. The relevant movement between the exterior tube (Element A) and the interior shaft (Element B) is carried out by an elastoplastic flexural deformation of the superimposed blades that connect crosswise elements A and B. The number and the dimensions of superimposed blades as well as their elastoplastic properties define the constitutive law of the diagonal bars on an axial load. Due to the possibility of the device to enter the interior shaft into the exterior tube and also to leave the one from the other, the device is capable to receive part or all the horizontal floor relative displacement. There is also a provision for a restraint bolt (stoppage bolt). This bolt is made of high yield steel, and can slide inactively through an appropriately selected oval hole at element B. 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) eliminate any additional compression forces on the diagonal elements and allow only tensional forces to be developed ($d_c>d_t$). The study of the restraint bold was not priority of this paper.

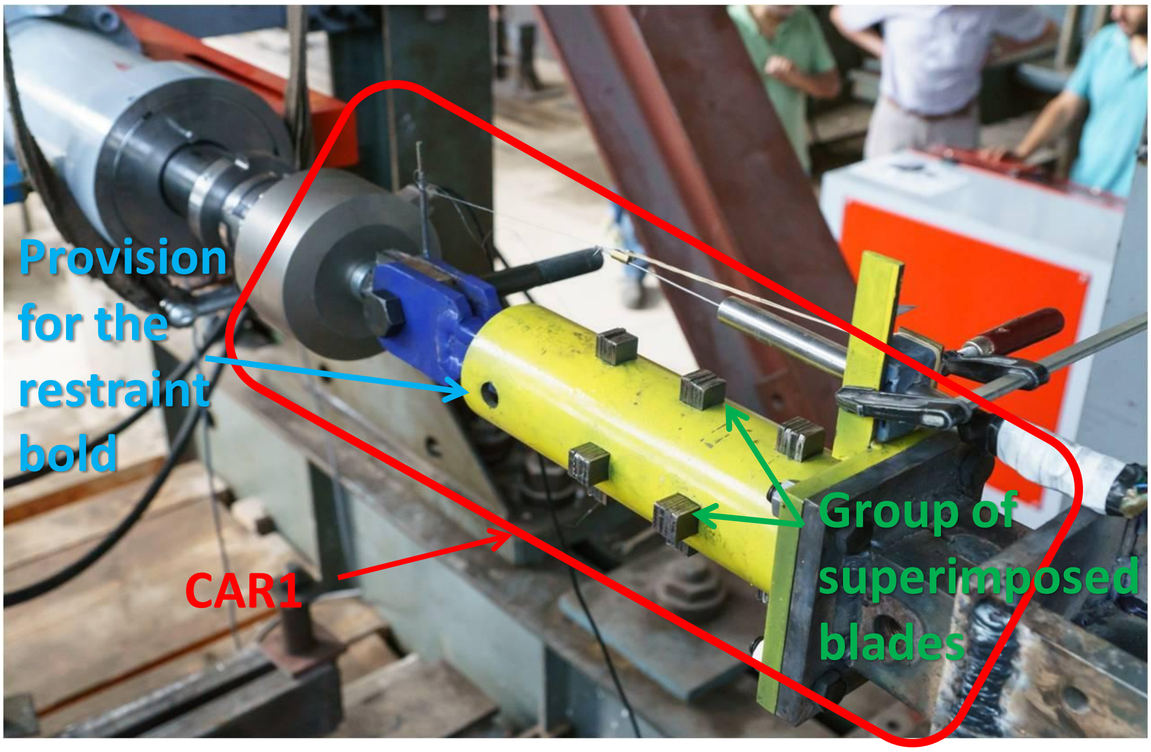

Figure 1. The proposed steel device CAR1.

The device CAR1 can be used on new or existing structures, on steel or R/C structures and can easily be adapted to the particular demands of structures. However, it can be installed in a variety of ways which include using them in single or cruciate diagonal braces.

The advantages of the proposed device are distinguished bellow:

a. By the use of the proposed device the load carrying capacity of the strengthened frame is increased by a constant, predefined, level through simultaneously friction and yield.

b. Also by the use of the restraint bold a supplemental strength and stiffness is provided after a predefined level of deformation, only in the tensile braces. When the restraint bold is activated, the device is locked, offering thus additional stiffness/resistance, control of the axial forces in the diagonal steel braces and limitation of the structure's displacement.

c. The strengthening level can be easily adjusted and changed during the years of existence and operation of structures. This can be achieved by replacing the superimposed blades with others (different material, thickness, friction).

3 EXPERIMENTAL SET UP

3.1 Material properties

A standard test has been carried out in order to establish the basic material properties of the superimposed blades (Figure 2) [13]. These experimentally derived material properties were utilized in the subsequent numerical study. The grade of the steel of the blades was S235. The experimentaly derived Young's modulus E, Yield Stress σy and maximum Stress σu are reported in Table 1.

Figure 2. Standard experimental test to establish the material properties of steel blades.

mass density [g/cm^3]	7.80
yield strength [MPa]	220.00
Young's modulus [GPa]	210.00
Poisson's ratio	0.3

Table 1. Main physical and mechanical properties of the steel superimposed blades.

3.2 Device CAR1 set up

A full-scale device was fabricated and experimentally investigated under cyclic loading. The experimental sequences, as it previous mentioned, were conducted at the premises of Laboratory for Strength of Materials and Structures of Aristotle University of Thessaloniki. The specimen details of the experiment are depicted in Figure. 3. The load of the actuator was controlled with a 100kN capacity load cell under displacement control. Two Linear Variable Differential Transformers (LVDT) were positioned at each side of the longitudinal axis of the device CAR1, which measure the relative movement of the interior shaft to the exterior tube. All data was recorded and stored in a digital data system via a computer. The present experiments were conducted with two group of superimposed blades (for material properties see §3.1.).

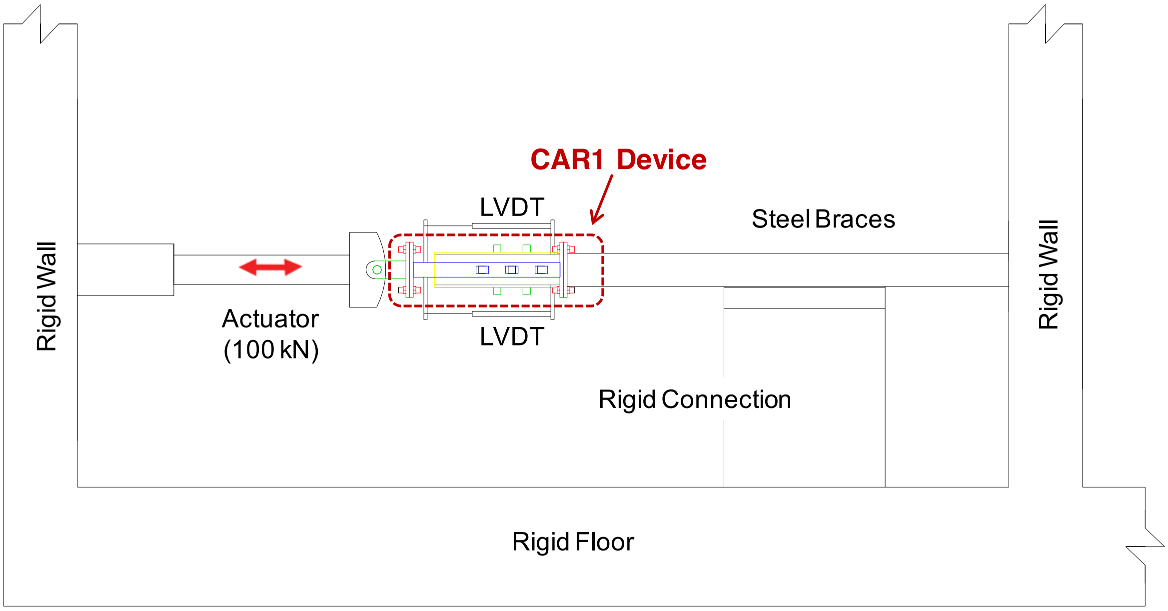

Figure 3.Spaciment details of the experimental sequences.

Quasi-static cyclic tests were carried out in order to ascertain the behaviour of the proposed novel device CAR1 toward the absorbed seismic energy. Totally two groups of experimental sequences have been conducted. For both sequences, two group of superimposed steel blades were tested. The first group of tests consists of 5 rectangular steel blades, each 4mm thick, while the second consists of 4 rectangular steel blades with thickness equal to 5mm.

The first group of experiments (5x4mm blades) was executed with two different loading rates. The first sequence is a monotonic loading with target load equal to 80kN with a rate of 18kN/minute equivalent to relevant displacements 13mm, while the second sequence is 60-cycle displacement control test with target displacement that varies from 0.5 mm up to 11 mm and with a rate of 3mm/minute (Figure 4). The tests of the second group were performed similarly with two different loading protocols. The first loading sequence is a monotonic load-control test with target load equal to 60kN and a rate of 14kN/minute equivalent to relevant displacements 13mm, while second sequence is a 50-cycle displacement control test with target displacement starting from 0.5 mm up to 9 mm and a rate of 3mm/minute (Figure 5).

Figure 4 shows the hysteresis loops that emerged from the experimental sequences of the first group. (5x4mm blades) The monotonic sequence is indicated with a black line, while the cyclic loading with a green line. The area within a hysteresis loop is equivalent to the amount of seismic energy that the device is dissipating. It is observed that the shape and consistency of the hysteresis loops remain constant during the repeated cycles, which proves that the device CAR1 is effective to dissipate seismic energy whereas it will not break during the repeated cycle loading. The proposed device CAR1 dissipated energy due to (i) the plastic strain of the superimposed blades during the cyclic loading sequence and (ii) due to the sliding-friction mechanism that is developed in the interface between the 5 superimposed blades

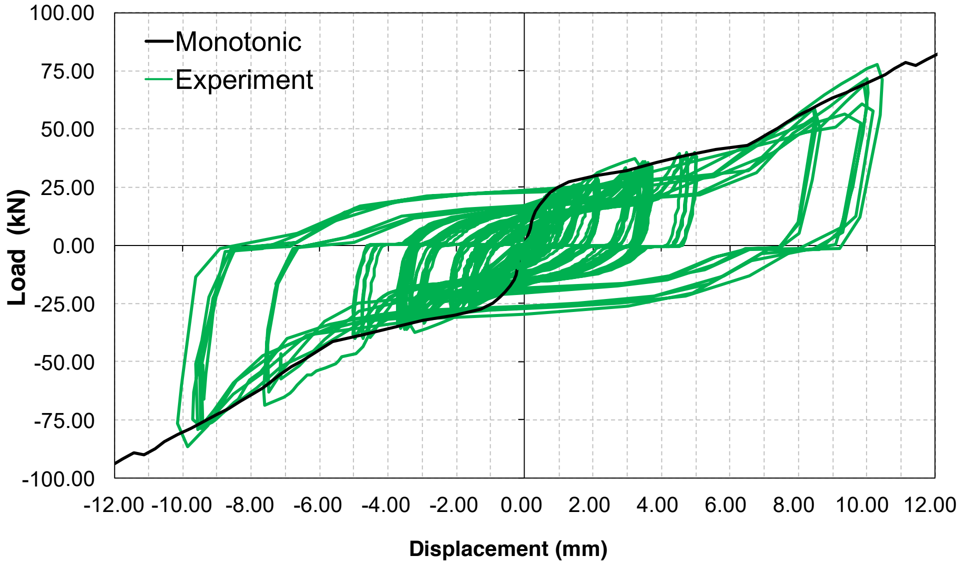

Figure 4. Hysteresis loops of the CAR1 device with 2 group of rectangular steel blades with thickness equal to 5mm.

Figure 5 presents the hysteresis loops that emerged from the experimental sequences of the second group. (4x5mm blades) Similarly to the previous groups of tests, the monotonic sequence is indicated with a black line, while the cyclic loading with a green line. The area within a hysteresis loop is equivalent to the amount of seismic energy that the device is dissipating. It is observed that the shape and consistency of the hysteresis loops remain constant during the repeated cycles, which proves that the device CAR1 is effective to dissipate seismic energy whereas it will not break during the repeated cycle loading. The comparison between the monotonic loading and the cycling loading shows that the monotonic loading is capable of reproducing the inelastic response of the cycling loading.

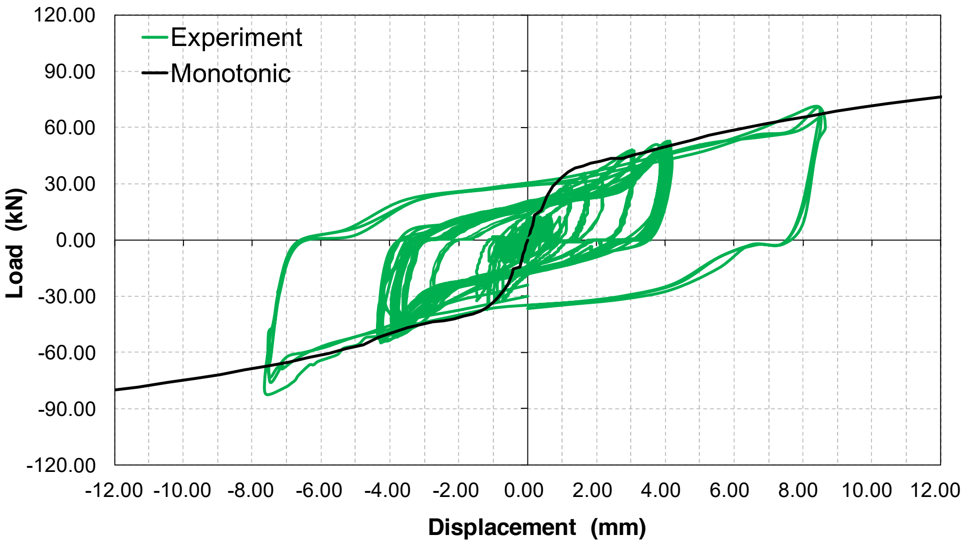

Figure 5. Hysteresis loops of the CAR1 device with 2 group of rectangular steel blades with thickness equal to 4mm.

The resulting monotonic curves are almost following the peak load values of the cyclic hysteresis curves for both configurations depicted in Figs 4 and 5. From both figures it is derived that the monotonic curve follows the envelope of the cyclic response of each device. Therefore, the monotonic loading curve can be reliably used to assess the stiffness and strength of the proposed device.

4 FE MODELING

The general purpose FE software ABAQUS was employed to generate FE models to simulate numerically the behavior of the device CAR1. It was selected to use an explicit dynamic solver because this allows the definition of very general contact conditions for complicated contact problems, without generating numerical difficulties. The explicit dynamics analysis procedure is based upon the implementation of an explicit integration rule together with the use of diagonal (“lumped”) element mass matrices.

To the comparison with the Standard, the explicit dynamic solver is computationally inefficient for quasi-static problems if real time is used, because the time needed to finish an analysis is proportional to its duration. However, it is often possible to scale the real time to a very small time period if the response of the structure remains basically static. According to classical dynamic theory, when a dynamic system is subjected to a linearly rising load, its response can be approximately treated as static if the duration of the loading stage is large compared to the natural period of the system. For solving this problem, check the ratio of kinetic to internal energy can be used to check if the structure has failed and the analysis is continuing simply as dynamic motion. It is stated in the ABAQUS/Explicit manual that the procedure is quasi-static if the ratio of the kinetic energy to the internal energy is less than 2%. Any responses which have an energy ratio larger than this should be treated as dynamic and removed from the results.

Several simulations were conducted to identify the best meshing. For the explicit method, blades and interior shaft are meshed using 3D reduced integration solid element **C3D8R** (eight-node bricks), while exterior tube is meshed using 3D solid element **C3D4** (four-node tetrahedron) available in ABAQUS. The final mesh has 8126 elements and it resulted in a solution that correlated with the experimental results. The uniaxial stress–strain relation of the blades, exterior tube and interior shaft are modeled as elastic with Young’s modulus (Es) and Poisson’s ratio (v) of which typical values are 200 GPa and 0.3, respectively. Plastic behavior are defined in a tabular form, including yield stress and corresponding plastic strain.

The surface-to-surface contact formulation technique with small sliding between the contacting surfaces was chosen. The contact definition includes the specification of two surfaces, one acting as the ‘‘master’’ surface and the other as the ‘‘slave’’ surface. The contact algorithm searches whether the nodes of the slave surface are in contact with the nodes of the master surface and enforces contact conditions in an average sense over a region of slave nodes using a Lagrange multiplier formulation. A friction coefficient equal to 0.2 [14] was assumed between the contacting surfaces.

5 COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

Fig. 6 plots - Force versus Relevant Displacement by the FEM analyses along with the experimental hysteresis of the two sequences. Green lines illustrate hysteresis loops of experiments, while red lines show hysteresis loops of the Finite Element Models. The FEM predicted values for the load and displacement are in very good agreement with the corresponding experimental ones. The comparisons between the FEM analyses and the experiments show that the proposed FEM model is capable of reproducing the inelastic response of the CAR1 device. Therefore, it is a reliable tool for the simulation of the hysteretic behavior of the CAR1 device and can be used in further studies in order to investigate the effect of various parameters. In addition, the monotonic loading curve (experimental or numerical) can be reliably used to assess the stiffness and strength of the proposed device.

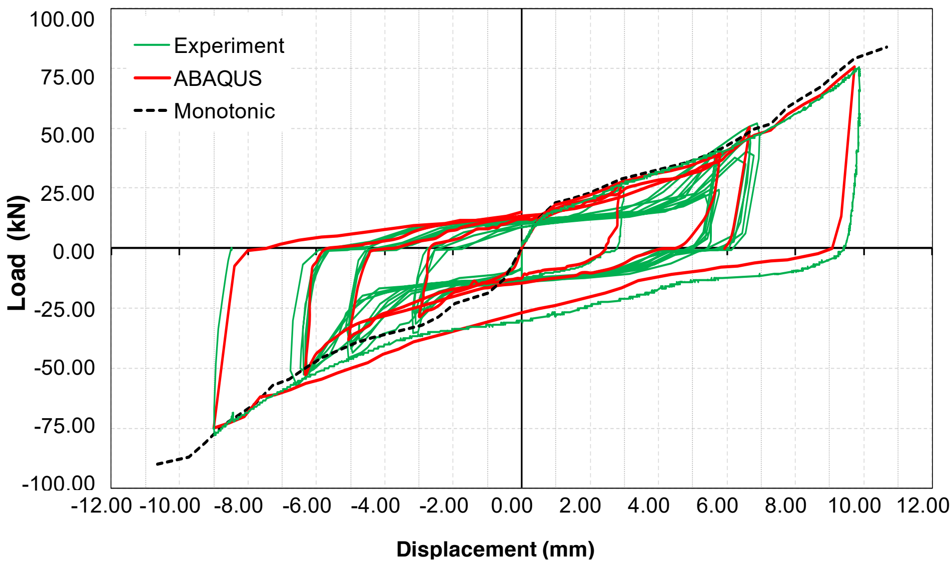

Figure 6. Comparison of the experimental and the numerical force–displacement hysteresis of the device CAR1 with2 group of rectangular steel blades with thickness equal to 5mm.

6 CONCLUSIONS

In the current study, an innovative device (CAR1) for the seismic upgrade of existing and new, either steel or R/C buildings, has been recently experimentally investigated and developed at the premises of Laboratory of Experimental Strength for Materials and Structures of Aristotle University of Thessaloniki.

Based on the findings of the present investigation, the following conclusions are drawn:

1) Device CAR1 is a reliable passive energy dissipation device, which can be used in new or existing structures and minimize the probability of structural failure against almost any external load. Based on the shape and consistency of the hysteresis loops obtained from the tests, it showed that the overall behaviour is remaining constant under the repeated cyclic loading sequence. In addition the proposed device is not failing. The device CAR1 dissipated energy due to (i) the plastic strain of the superimposed blades during the cyclic loading sequence and (ii) due to the friction forces.

2) The developed non-linear FEM models can be reliably used to assess the behaviour of the proposed anti-seismic steel device CAR1, since they are capable to track down the hysteretic behaviour and predict the deformed shape of the device with a good accuracy.

3) The comparison between the monotonic loading and the cycling loading shows that the monotonic loading is capable of reproducing the inelastic response of the cycling

loading. Therefore, the monotonic loading curve can be reliably used to assess the stiffness and strength of the proposed device.

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