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Finite element modelling of an innovative passive energy dissipation device for seismic hazard mitigation

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ABSTRACT

Nonlinear finite element analyses of an innovative passive energy dissipation device, referred to herein as CAR1, were conducted to investigate its behavior to dissipate seismic energy. The investigated device belongs to the passive energy dissipation systems, as it doesn't require external power to generate system control forces. It can be used on new or existing structures and can easily be adapted to the particular demands of structures. It can be installed in a variety of ways, including use in either single or cruciate (X) diagonal braces in building frames. Moreover this device has the advantages to provide (i) additional stiffness (ii) dissipation of seismic energy, (iii) as well as control of the axial forces that are developed at the diagonal steel braces. The main part of the device CAR1 is the groups of superimposed blades, which dissipate seismic energy through simultaneous friction and yield. The number and the dimensions of the blades as well as their elastoplastic properties define the constitutive law of the diagonal bars under axial force. To this purpose a finite-element micromodel of the device is formulated and used, by considering contact interface conditions between the blades. The analytical investigation is carried out through an extended comparative parametric study and is focused on the quantitative influence of certain simplified modelling assumptions and several critical modelling parameters on the response of the system. The present paper delineates a set of systematic procedures for finite element model calibration and parametric evaluation that enable robust simulation of the device CAR1 under quasi-static cyclic loading using explicit time-stepping dynamic analysis procedure.

1. Introduction

The safety of constructions (existing or new) is one of the major priorities of engineering globally. Braced frames constitute a seismic protection system with enhanced seismic performance due to their high stiffness and strength. However, conventional braced frames, exhibit a degrading hysteretic behavior which results in damage, fracture and increased collapse potential [1,2]. Therefore, many efforts have been made to create devices that can dissipate a large percentage of the seismic energy without belonging to the supporting structure of the constructions. The main advantages of these, is the possibility of easy replacing and repairing. Using devices, which belong to the passive energy systems, is one of the effective and applicable methods to improve the seismic performance of structures. These devices can be categorised in friction dampers [3,4], metallic dampers [5] and viscoelastic dampers [6,7]. Their effectiveness for seismic design of building structures is attributed to minimizing structural damages by dissipating the structural vibratory energy and by dissipating it through their inherent hysteresis behavior [8–10].

In the present work attention is focused on the braced frames protection. Balendra et al. [11] proposed a new fuse element, with high stiffness and suitable ductility, as knee braced frames in order to prevent buckling. A few years later, Balendra et al. proposed two-level passive control systems based on a knee brace and a slotted connection; in small forces by energy dissipation through friction, while in strong earthquakes through plasticity [12]. Franco et al. [13] presented a new yielding damper based on plastic properties of the metals. In another study, Papadopoulos in 2012 proposed a new metal frictional device, which has 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 [14]. Another way to protect braced frames is by using buckling-restrained diagonal braces, as they have the same load deformation behavior in both compression and tension and higher energy dissipation capacity with easy adjustability of both stiffness and strength [15,16]. In the last few decades, buckling-restrained braced frames have become increasingly popular especially in Japan for their good seismic performance [17]. In addition, many researchers have proposed the use of

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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 [18–24].

In this study a novel energy dissipation device, referred to herein as CAR1, is analyzed. Such a device comprises four distinguished parts; an external cylindrical ring, an internal prismatic holder, several groups of superimposed blades that are responsible for the transfer of forces between the aforementioned parts and the restraint bolt. We focus our study on a set of systematic procedures for finite element model calibration and parametric evaluation that enable robust simulation of the innovative passive energy dissipation device under cyclic loading with high fidelity using explicit time-stepping time-history analysis methods. The accuracy of the 3D model was assessed against the experimental results [25,26] and the validated model was subsequently used to generalize the experimental findings and to study the effects of various parameters on the response of the device CAR1. Based on the experimental and computational results, a micro-investigation locally in regions of high importance is permissible. In this way, results come out that are harder to obtain experimentally.

2. Description of the innovative passive energy dissipation device

The innovative energy dissipation device has the codename CAR1 and belongs to the passive energy dissipation systems, as it doesn't require external power to generate system control forces. The device takes its name due its triple ability: (i) to Control the axial forces that are developed at the diagonal steel braces, by the appropriate selection of the number and dimensions of the superimposed blades, their elastoplastic properties, as well as the friction coefficient at their interface, (ii) to Absorb seismic energy and (iii) to Retain the plastic displacements up to a desired level, due to the existence of the restraint bolt [25]. The number 1 of the acronym refers to the fact that the analyzed system corresponds to prototype # 1 of the device fabricated at the Laboratory of Structural Analysis & Dynamics of Structures at Aristotle University of Thessaloniki. The device has variable behavior 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 was proposed by Papadopoulos et al. [27] and it consists of 4 main elements, as illustrated in Fig. 1a. The exterior tube, the interior shaft, five groups (or more) of superimposed blades and the restraint bolt. Observing the cross section of the device CAR1 (. 1b), it is visible the slight curvature in the interior shaft of the device. These curves help blades to become curved. 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 braces under axial load. Due to the ability of the device to enter the interior shaft into the exterior tube and also to leave the one from the other, when it is install in the diagonal brace, the device is capable to receive part or all the horizontal floor relative displacement, without developing plastic deformation at the diagonal brace. 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 actual plastic deformations of the superimposed steel blades to keep constant as the axial tension force of the diagonal is further increasing. The activation of the restraint bolt allows the transfer of an additional axial force 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 ($d_c > d_t$). The connection of the innovative device CAR1 with the structure is carried out by a rigid connection of the exterior tube with the steel diagonal brace and by a hinge connection of the interior tube with the joint of the frame (Fig. 1c).

The device can be used on new or existing steel or RC structures, and can easily be adapted to the demands of the structure in question. It can be installed in a variety of ways, including use in either single or cruciate (X) diagonal braces. The proposed steel device contributes towards an increase of the seismic capacity of the building frames, since its operation is based on the following four discrete stages (Fig. 2):

Stage A-B: The yielding in bending of the superimposed steel blades is not activated, frictional slipping of the blades usually occurs and the diagonal steel brace is operating in the elastic area until reaching the predetermined load Fs.
Stage B-C: The device operates as a mechanism. In this step yielding in bending and frictional slip of the superimposed steel blades occur, but the diagonal steel brace remains in the elastic area.
Stage C-D: The device is locked (C–D) due to the activation of the restraint bolt. Therefore, the tensile diagonal steel brace is fully activated. More specifically, the locking of the device causes an increase of the tensile axial force of the diagonal steel brace and an additional lateral strength of the frame is presented. So, the tensile axial load of the diagonal steel brace is increased after the locking of

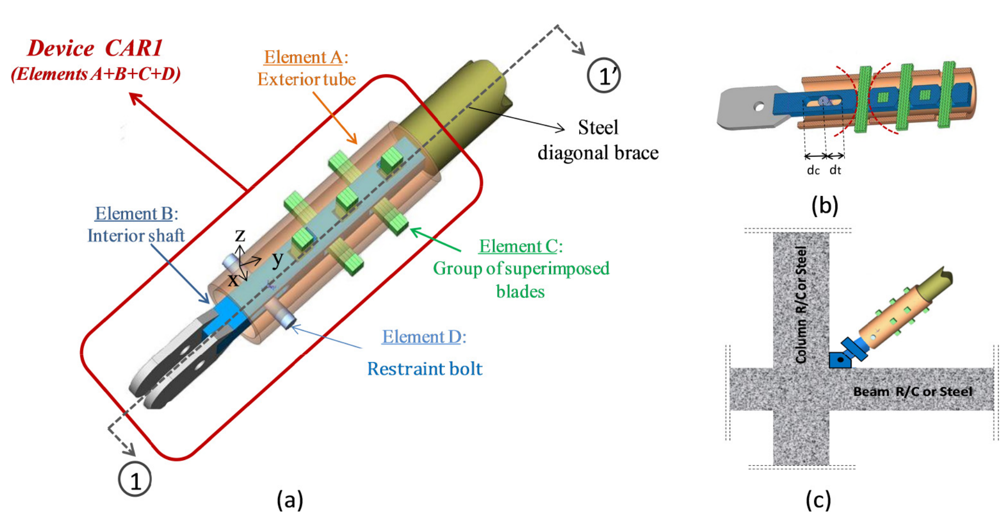

Fig. 1. (a) The proposed steel device CAR1, (b) the cross section 1–1′ of the device CAR1, (c) connection of device in RC or Steel structures.