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Development of a novel combined system of deformation amplification and added stiffness and damping: Analytical result and full scale pseudo-dynamic tests

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ABSTRACT

This research presents the theoretical and experimental development of a new system called: Amplified Added Stiffness and Damping (AASD), which is a combination of an amplifying mechanism and a frictional self-centering damper capable to support large deformations. The operation of the damper is based on the well-known straps with friction principle. A first conceptual single acting device used for validating this principle and comparing the behavior of commercial straps (polyamide, aramid and carbon fiber) was built. Subsequently, two double acting prototypes with carbon fiber straps were built, since this material showed the best performance. Both, the conceptual device and the two prototypes (named as I and II) have shown very stable constitutive relations. Because of its greater simplicity, the "prototype II" represents a technically and economically attractive solution. Furthermore, due to its ability to accommodate large deformation in both directions, it is an ideal device to combine with amplifying mechanisms. A parametric numerical analysis performed on a single-story structure with AASD, showed a wide range of parameters of AASD leading to reductions greater than 40% on displacement response. A full-scale asymmetric one-story steel structure equipped with one AASD was built. The structure was subjected to a variety of tests using a multi-axis pseudo-dynamic equipment recently installed in the Laboratory of Structural Engineering of the Pontificia Universidad Católica de Chile. So far, the authors didn't find references of a full scale pseudo-dynamic test of this nature. The structure without AASD presented a non-linear behavior mainly due to sliding of the bolted connections of the beams. Pseudo-dynamic seismic response tests were performed considering an artificial ground motion acting in one direction. As expected, and due to the mass eccentricity (20% of its plan length), high concentration of deformations in the flexible edge of the structure without AASD was observed. Conversely, the structure with AASD showed a great plan deformation uniformity (torsional balance), with reductions of nearly 40% in maximum edge deformation, which is consistent with the parametric analysis results. The eccentric lever arm used as amplifying mechanism, which have large amplifying ratio $\alpha = 11$, worked in great accordance with numerical simulations.

1. Introduction

The application of the classical concepts of vibration control by mean of passive energy dissipation devices (EDD), has been widely developed in the field of earthquake engineering [1–3]. However, the use of EDDs has not achieved widespread acceptance in professional practice. This situation could be attributed to two causes: (1) the cost of implementation of the EDDs is still relatively high; and (2) reductions in the maximum inter-story deformation (for example) rarely exceeds 30%. In other words, the cost/benefit ratio is not yet attractive enough to designers and owners, especially in developing countries. Clearly, steel framed structures take more advantage of the use of EDDs, especially medium and high rise buildings located in soft soils (i.e. narrow band seismic motion). On the other hand, reinforced concrete walled structures located in firm soil (i.e. broad band seismic motion) show greater difficulties in the successful implementation of EDDs. In earthquake engineering applications, the most commonly used energy dampers are: (1) hysteretic metal dampers [4–12]; (2) frictional dampers [13–18]; and (3) non-linear viscous dampers [19–21]. While few applications in real structures are known, they have also proposed many semi-active devices for control of vibration in structures.

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Among them we can mention a system controlled by an electromechanical actuator capable of independently varying stiffness (SAIVS) [22], damping (SAIVD) [23], or frictional force (SAIVF) [24]. Moreover, it has recently been proposed a non-linear passive system called adaptive negative stiffness (ANSS) [25,26] designed to introduce an effect of "apparent weakness" in the structure due to the unloading of a pre-compressed spring.

Despite the variety of EDDs, the economic factor remains very important, being necessary to optimize the quantity, unit cost, and its location within the structure. For this reason, and due to its simplicity and (relative) lower cost, frictional and metal devices are currently the most used ones in professional practice.

To overcome the problem of small inter-story deformations, various amplifying mechanisms have been proposed, among which we can mention the "toggle brace damper" (TBD) [27–30], "scissor-jack" [31], "lever-arm" [32], hydraulic amplification device [33], and amplification systems based on pinions of different diameters [34]. Of all the devices mentioned above, the TBC is probably the most studied, both analytically and experimentally. Furthermore, it is the only amplifying mechanism which real applications have been reported [35,36]. In Ref. [27], a shaking table test of a one-story half-scale model is presented. The results of this study show that the TBD is an easy to design mechanism, of relatively simple construction, and capable to reach real amplification values between 2 and 3.

On the other hand, the EDDs has arisen as one of the most advisable solutions to control deformations in asymmetric structures. There is a large number of numerical studies regarding the effectiveness of EDDs to control torsional effects in asymmetric structures subjected to earthquakes [37–39]. In the context of linear single story structures with viscous damper, the so-called "mirror rule" [37] was the first criterion proposed in the literature related to the optimal plan location of the EDDs. This concept suggests that the center of supplemental damping (CSD) and the center of stiffness (CS) should be placed at equal distance and in opposite side from de center of mass (CM). Later, the "torsional balance" concept was proposed as a general design criterion for linear and non-linear asymmetric structures with linear and non-linear EDDs [40–42]. Torsional balance is defined as the property of an asymmetric structure that leads to equal deformation demand in structural members equidistant from the geometric center (GC) of the structure plan. By mean of shaking table tests of small-scale asymmetric models [43,44], the torsional balance concept has been experimentally proved. Nevertheless, full-scale experimental studies of asymmetric structures with EDDs subjected to seismic excitations have not been reported in the literature.

This research presents the theoretical and experimental development of a new system called: Amplified Added Stiffness and Damping (AASD) which is a combination of an amplifying mechanism and a frictional self-centering damper capable to support large deformations. The work is divided in four parts: (1) main ideas and proof of concept testing of the damper device; (2) developing and testing of two prototypes; (3) numerical parametric analysis of a single-story structure with AASD; and (4) pseudo-dynamic tests of a full scale asymmetric one story steel structure with and without AASD. The main hypothesis of this work is that the AASD is an efficient alternative for structures based on frames, as well as, and especially in structures based on reinforced concrete walls (typical building in Chile), where the relatively small story-drift makes it difficult to implement EDDs.

2. Main ideas and proof of concept testing

The system proposed in this research is based on the simultaneous amplification of deformations and forces. Deformations amplification is achieved by an eccentric lever arm system (ELAS), whose principle of operation is described in detail in Ref. [47]. Force amplification is achieved using the well-known principle of pulleys with friction operation. For this purpose a strap around a set of cylindrical bodies are used, as schematically shown in Fig. 1, where the relationship between inner and outer (tensile) forces equals to:

$$T_{n+1} = T_1 \nu = T_1 \exp\left(\sum_{k=1}^{n} \mu_k \beta_k\right) \tag{1}$$

where T_1 and T_{n+1} are the inner and outer forces, respectively; $\nu = \exp\left(\sum_{k=1}^{n} \mu_k \beta_k\right)$ is the force amplification factor; μ_k and β_k are the friction coefficient and the contact angle in the k-th cylinder, respectively; and n is the number of connected cylindrical bodies. Obviously, to exploit the effect of exponential amplification, an inner force T_1 must be generated.

Fig. 2 shows a scheme of the first device manufactured in order to test the concept (conceptual device). It is formed by a strap that surrounds a series of cylindrical steel tubes. These tubes are welded to a metal U-shaped frame consisting of two parallel steel angles and a backing steel plate. One end of the strap is connected to a tension spring, whose functions are: (i) generate the inner force T_1; and (ii) return the strap to its initial position.

As shown in Fig. 3, for an ideally inextensible strap, the force–displacement relationship would be (ideally) triangular, that is:

$$T(\Delta, \dot{\Delta}) = (k_s \Delta)\nu = k_L \Delta \qquad \text{if } (\Delta\dot{\Delta}) > 0 \tag{2a}$$

$$T(\Delta, \dot{\Delta}) = \frac{(k_s \Delta)}{\nu} = k_U \Delta \qquad \text{if } (\Delta\dot{\Delta}) < 0 \tag{2b}$$

where $T(\Delta, \dot{\Delta})$ is the outer force; Δ and $\dot{\Delta}$ are the displacement and velocity of the free end of the strap, respectively; $k_s\Delta$ is the spring force (inner force); k_s is the spring stiffness; $k_L = k_s\nu$ and $k_U = k_s/\nu$ are the loading and unloading stiffness, respectively. Because the stiffness of the device is variable but always positive, it produces a simultaneous increase in stiffness and damping. Note that the above equations are formally identical to those of the well-known Energy Dissipating Restraint (EDR, [16]) device, one of the first self-centering devices proposed in the literature.

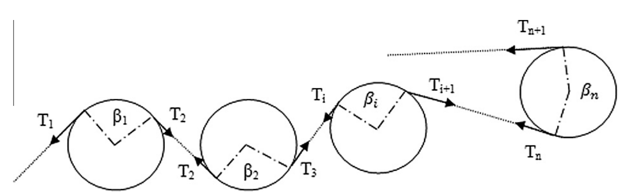

Fig. 1. Set of pulleys with friction and strap with discontinuous contact.

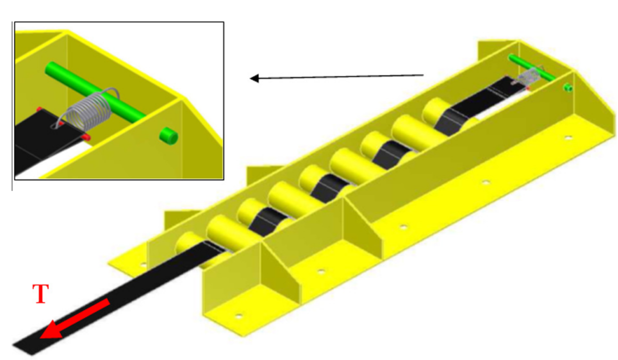

Fig. 2. Model of the device used for proof of concept tests.