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Experimental and analytical characterization of steel shear links for seismic energy dissipation

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ABSTRACT

This paper describes the experimental investigation on a newly designed steel shear link (SL) for seismic protection of civil structures. It is a low-cost hysteretic device, realized from a single steel plate where variable thickness is given through milling. It has been already adopted for several applications in South America, both for new constructions and seismic retrofit of existing buildings. Even small variation of device's geometry can significantly modify its mechanical behavior, both in terms of strength and stiffness, making such devices very appealing for the flexibility in terms of design solutions.

SL device is conceived to be connected to the main frame through bolted connections and mounted on a supporting brace. In particular, slotted holes on one edge of the damper prevent the device from transmitting shear to the upper beam during the seismic excitation. A couple of specimens for each of 5 different geometries has been tested, for a total of 10 tests. Two different boundary configurations have been considered, analyzing results of fully-tightened or not fully-tightened bolts in correspondence of slotted holes. The set-up system has been properly designed to apply forces up to 1000 kN, to be able to accommodate and test the largest specimens of the set. The paper presents the experimental results and data processing concerning analysis of deformation process, hardening behavior and collapse. The main features of the control devices are highlighted, above all, the high dissipative capability that is mainly due to the particular shape of the steel damper, which leads to a high buckling resistance.

1. Introduction

Shear link dampers belong to the family of hysteretic passive control devices. They can provide additional source of energy dissipation through metals yielding mechanism, when properly introduced within a frame structure. The first versions of this type of device was used for eccentrically braced frames (EBFs) [1]. The latter were conceived as intermediate steel structure systems between dissipative but excessive deformable moment resisting frames (MRFs) and stiff and brittle concentrically braced frames (CBFs). EBF systems are significantly stiffer than MRFs due to the introduction of braces and supply an additional source of energy dissipation through shear and/or bending in a portion of beam called "link". The longer or shorter link's length respectively identifies a moment or shear link primary behavior.

Many different steel dampers have been proposed and investigated in literature, exploring different materials, geometric shapes, manufacturing process and connection configurations to the structure [2,3]. The simplest shear link is a single steel plate, generally welded to the structure, indicated in literature as shear panel damper (SPD) [4,5]. Low-yield steel [6] or aluminum materials [7,8] have been used for alternative SPD. Actual dissipation capacity mainly depends on inelastic excursions that device can sustain even for small vibrations.

The family of flexural steel dampers is wider, including the most popular ADAS, TADAS, slit dampers, honeycomb dampers. Added Damping And Stiffness (ADAS) device was first investigated by Bergman et al. [9] and Whittaker et al. [10]. It is composed by steel X-shape plates connected in parallel at the top and at the bottom to rigid elements so that the rotation is not allowed. The particular shape of steel plates ensures a uniform flexural yielding in the element. Alternatively, Triangular Added Damping And Stiffness (TADAS) device is a triangular steel plate [11] that subjected to a perpendicular lateral force undergoes uniform yielding along the height thanks to linearly

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increasing moment. The steel slit damper (SSD) is a standard I-section with a number of slits cut from the web. The final shape is an alternation of struts and slits, achieving a vierendeel truss arrangement [12,13]. Honeycomb steel damper was developed by Kobori et al. [14] with the aim of increasing energy absorption of high-rise buildings. This device consists in a steel plate with honeycomb-shaped openings, which generate X-shaped struts.

All the aforementioned devices are generally placed between chevron braces and an upper beam. In some cases, hysteretic dampers can be placed in series with diagonal braces, so providing energy dissipating element in concentrically braced frames. This is the case of a particular cast steel yielding fuse, also known as scorpion yielding connector (SYC) [15], which dissipates energy through the cyclic inelastic flexural deformation of the SYC's cast steel yielding fingers. The overall fuse's aspect resembles ADAS or TADAS device, with the difference that SYCs are manufactured through steel casting process.

A different group of yielding dampers dissipate cyclic loads-induced energy through axial deformation. This is the case of Buckling Restrained Braces (BRB), developed by Clark et al. [16], which consists in an unbonded core steel brace encased in a concrete-filled steel tube to avoid buckling mechanism when compressed.

A wide number of experimental tests performed on both types of dissipative link has shown that shear links can achieve larger plastic rotations and greater energy dissipation than moment links [1]. In general, shear links' common features observed are stable hysteretic curves, significant strain hardening and energy dissipation capacity. These remarkable characteristics encourage further investigation of this kind of passive device, on one hand trying to optimize some important features such as the manufacturing process and the cost of the device, on the other hand promoting its use with experimental campaigns that highlight the actual effectiveness for structural control.

This paper presents the experimental analysis of a particular shear link damper, referred to as Shear Link Bozzo. It consists of a metallic yielding device first advanced at the University of Girona, Spain, in 1997 [17–19]. It will be widely described in the next section where it will be briefly referred to as SL damper. is particularly advantageous thanks to its flexibility in covering a wide range of force capacities, that makes it adaptable to different levels of demand. The basic idea behind the SL dissipator is providing local ductility, while avoiding local buckling in a simple, manufactured controlled and cheap way. The simplicity of SL dampers' geometry makes them particularly suitable to be adapted to different arrangement within the structure. The typical and most used installation mode for SLs is between chevron braces and upper beam, as schematically shown in Fig. 1. Although, the first use of such devices was to protect infill masonry walls [20]. The authors also investigated the alternative use of SL dampers to protect precast RC structures, inserting devices within diagonal braces [21].

Nowadays, several applications have been developed and carried out using these devices: more than one thousand of SL dampers have been installed worldwide, mainly in RC buildings in Mexico, Peru and Ecuador, for new constructions (Fig. 2) as well as for seismic retrofitting of existing ones (Fig. 3).

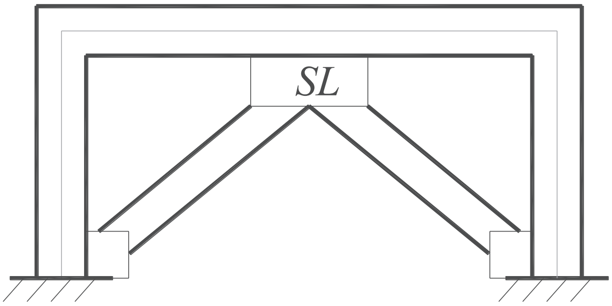

Fig. 1. Typical SL configuration within the structure.

Fig. 2. Installation of a SL for the new construction of Torre Ixtapa (Mexico).

Fig. 3. Installation of a SL for the seismic retrofit of hotel Ceibo Dorado after October 2016 earthquake in Ecuador.

2. Previous investigations on SL passive dampers

The SL device system consists of a metallic hysteretic damper realized from a hot laminated steel plate which is generally modeled so that to obtain an I-shape. The flanges of the device represent the stiffer parts and are employed to realize the connection to structural elements. Differently, energy dissipation is concentrated at the web where "dissipative windows" with reduced thickness are generated through a milling manufacturing process [20]. Wide ranges of SL's dissipation capacities can be obtained simply varying the height, width and thickness of the dissipative windows and web stiffeners. For this reason, different generations have been proposed and investigated both numerically and experimentally during last 20 years (Fig. 4), aiming at optimizing their mechanical performance.

The first experimental studies (Fig. 4a) were performed at ISMES S.p.A., in Bergamo (Italy) in 1997, where the first generation of SL devices was tested [22]. The flanges of the devices were welded to horizontal thick plates, constituting elements of connection to the machine, through high strength bolts. In the web, there was a unique column of dissipative windows with thicknesses between 1.5 and 2.0 mm, while flanges and other stiffeners were 15 mm thick. Four devices with different types of transition zone between the web and stiffeners were cyclically tested, all performing stable hysteretic behavior with significant strain hardening. It is worth to note that after severe damage of the dissipative windows, the SL devices continued to exhibit a stable behavior even with lower hysteretic curves corresponding to a flexural dissipative behavior (Fig. 5).

A further device belonging to the first SL generation was examined at the Laboratory of the University of Girona. Its shape was squatter than the previous and the main investigation was concerning web buckling. It was observed that the distortion angle γ, analytically evaluated as the ratio between the head displacement and the total dissipative windows' height, was quite close to the experimental strain