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Experimental tests on Crescent Shaped Braces hysteretic devices

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ABSTRACT

Crescent Shaped Braces, CSBs, are steel hysteretic devices which, thanks to their geometrical configuration, are characterized by an enhanced seismic behavior that makes them a promising alternative to conventional diagonal steel braces and other seismic devices such as Buckling Resisting Braces and Scorpions. The present work reports the results of the first experimental campaign devoted to assess the cyclic experimental behavior of CSBs. The main goals of the experimental campaign are: (i) to verify/compare the effectiveness of design formulas for the seismic design of CSB introduced by the authors in a previous research work and the predictions of a simplified non-linear model in terms of force-displacement envelop response; (ii) to assess the experimental non-linear cyclic behavior in terms of ductility capacity, energy dissipation capacity, failures.

1. Introduction

Energy dissipation systems for the mitigation of the seismic-induced effects have been developed over the last half century in order to raise seismic performance levels of constructions keeping costs reasonable [3]. They are usually classified in three main categories: active, semi-active and passive systems. Active and semi-active control systems are force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure [18]. Such systems require external power sources, which represents a significant limitation on their seismic applicability. Passive systems operate without external power supply and are activated by the motion (displacements and/or velocities) of the structure. Metallic and friction (hysteretic) dampers belong to the category of displacement-activated supplemental damping systems. Steel dampers take advantage of the hysteretic behavior of the material exceeding its yielding point. Particularly desirable properties of these devices are a stable hysteretic behavior, the ability in sustaining an adequate number of cyclic loading-unloading (low-cycle fatigue), long term reliability and low sensitivity to environmental temperature [18].

Since the mid-1970s, a considerable number of hysteretic devices have been developed and tested. According to Christopoulos et al. [3], the ones that have demonstrated a particularly desirable behavior are here briefly recalled. The Added Damping – Added Stiffness (ADAS) device, originally manufactured by Bechtel Corporation in the 1980s, is usually installed between the apex of a chevron brace and the underside of the beam. The Triangular Added Damping – Added Stiffness (TADAS) device, developed by Tsai et al. [21], is a variation of the original ADAS device which makes use of triangular plates as dissipative steel elements. In the mid-1970s, Lead Extrusion Devices (LED) were proposed in New Zealand [16] taking advantage of the stable and repeatable hysteretic behavior of a lead element. The Buckling Restrained Brace (BRB), as the unbounded brace manufactured by Nippon Steel Corporation in the early 1980s, consists in a steel member encased in a tube filled with concrete that prevents the buckling [2]. The Cast Steel Yielding Fuse (CSF) device, as the one manufactured by Cast Connex Corporation (under the commercial name of Scorpion Yielding Devices), is a steel device for concentrically braced frames that dissipates energy through inelastic flexural yielding of special elements. The system exhibits a full, symmetric hysteresis characterized by an increase in stiffness at brace elongations larger than the design level. This increase in stiffness is a result of the second-order change in geometry of the yielding fingers, each of which is shaped to promote the spread of plasticity along its entire length. This effect can limit peak drifts and residual drifts and mitigate the likelihood that, in the event of a large earthquake, the inelastic demand will collect at a single storey [8,9]. Recently, a wide experimental campaign aimed at assessing the effectiveness of two Energy Dissipating Bracing (EDB) has been carried out at the University of Basilicata (project JetPacs) [5]. In detail, the two EDB systems are: the Hysteretic Damper (HD) device and the visco-recentring device (so called SMA+VD). The HD devices are composed by ad hoc shaped steel plates in order to dissipate energy through flexural yielding and characterized by an elastic-plastic with hardening force-displacement response.

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The SMA+VD devices consist of the coupling of fluid viscous velocity-dependent energy-dissipating devices (VD) with a displacement dependent Ni–Ti shape memory alloy device (SMA), which are characterized by a symmetric flag-shaped force-displacement response.

In 2009, within the framework of Stiffness-Strength-Ductility design (a design procedure base on PBSD approach), some of the authors introduced a new hysteretic device, known as Crescent Shaped Brace (CSB), able to fulfill multiple seismic design objectives in terms of stiffness, strength and ductility and represented by mean of an objective curve [20]. Later on, the potential capabilities of CSB devices has been shown through an applicative example where a five-storey steel frame is designed according to the concept of "enhanced first storey isolation" inspired to the original concept of storey isolation proposed in the late 1960s [7]. The CSB devices placed at the ground floor, thanks to their peculiar geometrical shapes, are characterized by a lateral stiffness uncoupled from the yield strength and by an overall symmetric hysteretic behavior with a hardening response at large drifts (due to non-linear geometrical effects) which may prevent from global structural instability due to second-order effects (such as P-Δ effects).

In a more recent research work [14] the attention has been devoted in the study of the single device. Analytical and numerical studies devoted to the assessment of the non-linear mechanical and geometrical behavior of CSB have been developed, with a particular attention devoted to seismic design purposes. To complete the seismic assessment of the device, experimental tests on various scaled specimens have been carried out at the Structural Engineering and Geotechnical Laboratory (LISG) of the University of Bologna (Italy). In the present work, the main results of the experimental tests are presented.

2. The seismic behavior of Crescent Shaped Braces

2.1. The geometrical and mechanical properties of CSBs

The Crescent Shaped Brace (CSB) is a hysteretic steel device made by commercial steel profiles connecting two points of the structure (i.e. two consecutive stories when used as diagonal braces in framed structure). Based on their configuration and placement inside the frame structure, two global force-displacement responses could be typically observed: (i) asymmetric response of the single bilinear CSB device (Fig. 1a); (ii) symmetric response of the couple of two bilinear CSB devices (Fig. 1b).

The hysteretic force-displacement response of the single CSB device is strongly asymmetric due to non-linear geometrical effects: significant hardening response under lateral loads inducing tension in the brace, softening response under lateral loads inducing compression in the braces (Fig. 1a). On the contrary, two CSB devices inserted in a two span frame structure as displayed in Fig. 1b are characterized by an overall symmetric hysteretic response, given that one works in compression, whilst the other one works in tension. Such a global response remembers the desirable behavior of the Scorpion Yielding Device (see Fig. 10 of [9]. With reference to Fig. 2, the relevant geometrical and mechanical properties of a bilinear CSB device are listed below.

Geometrical properties of the single device in the initial configuration:

- length of each straight member L^*.
- inclination with respect to the horizontal direction θ_0 (L_0.
- indicates the horizontal projection of L^*).
- lever arm d_0, or its normalized version $\xi = d_0/2L_0$.
- cross-section height h.
- cross-section area A.
- in-plane and out-of-plane moment of inertia of the cross-section J and I, respectively.

Mechanical material properties (assuming a bilinear elastic-plastic stress–strain relationship):

- elastic modulus E;
- yield strength f_y;
- hardening ratio, r, as defined as the E_p/E ratio, where E_p is the tangent of the stress–strain curve after the yielding point.

2.2. The seismic design of frame structures equipped with CSBs

In previous research works by some of the authors, the mechanical behaviors of both a single device as subjected to cyclic lateral forces [14] and a frame structure equipped with CSBs [13] were investigated.

In detail, in the work by Palermo et al. [14] the attention was mainly focused in the study of the elastic behavior up to the first

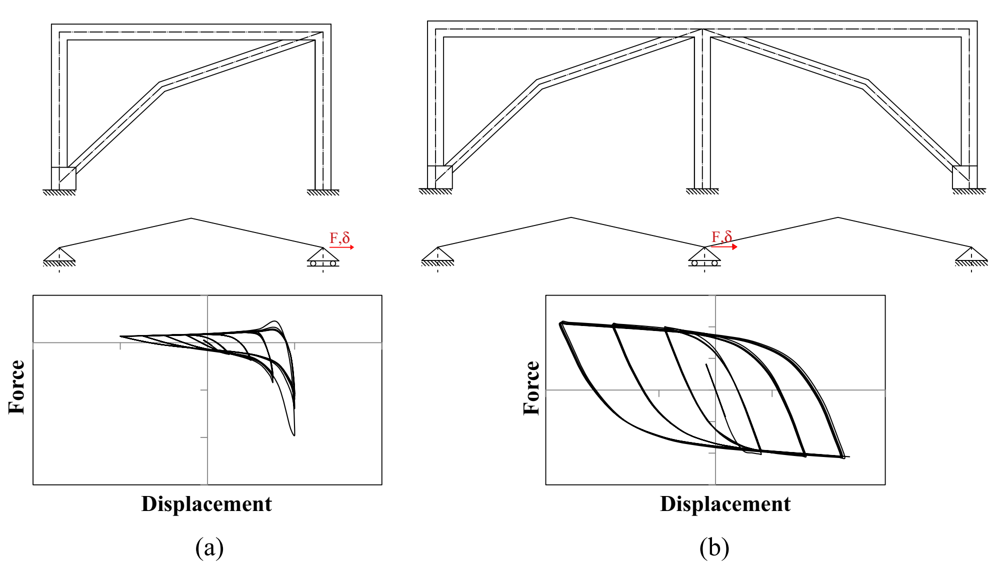

Fig. 1. (a) A bilinear CSB device inserted in a frame and its asymmetric force-displacement response; (b) two mirrored disposed bilinear CSB devices inserted in two frames and their symmetric force-displacement response (Adapted from Palermo et al. (2015)).