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EXPERIMENTS ON CRESCENT SHAPED BRACES

ANTOINE DIB, MICHELE PALERMO, LUCA PIERACCINI, STEFANO SILVESTRI,
GIADA GASPARINI, and TOMASO TROMBETTI

Dept of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Bologna, Italy

Different design strategies, within the Performance Based Design framework, have been proposed through the years in order to design a structure of high seismic performances, including seismic isolation, viscous dampers and hysteretic dampers. A new lateral-resisting device, referred to as Crescent Shaped Brace (CSB), has been recently proposed to be used for the story isolation of multi-story frame structures. The main property of the CSB is that its lateral stiffness is uncoupled from its yield strength so that the practical designer may choose them independently, unlike conventional diagonal braces whose lateral stiffness is directly proportional to the yield strength. Past studies were devoted to the development of analytical formula for the design of such devices and to the study (through numerical simulations) of their non-linear response. In the present paper, the main results of experimental tests conducted on scaled CSB specimens (monotonic tests, cyclic tests, pseudo-static tests) are presented in order to assess the seismic behavior of such devices. The results of the experimental tests are compatible with the analytical predictions.

Keywords: New damping device, Hysteretic dampers, Performance-based design.

1 INTRODUCTION

Studies devoted to develop seismic resistant structural solutions and reliable design procedure to overcome the complex characterization of a seismic action and the correspondent structural response have opened up new horizons for the structural engineer in terms of comprehending and designing structural systems which offer predetermined seismic performances (i.e., damage limitation and life safety prevention) while keeping construction costs reasonable.

The framework which formalize this basic idea is the Performance Based Seismic Design (Bertero and Bertero 2002), which introduced the concept of multiple performance objectives (or objective curve) obtained from coupling structural and non-structural performance requirements with various intensity levels of seismic actions. As a result, the building structure should behave in the desired way under both the frequent and rare seismic event.

A design strategy allowing the achievement of multiple performance objectives is based on the conceptual separation of the vertical resisting system from the horizontal resisting system. Clearly, in order to design a structure behaving closely to the desired "objective curve" (Palermo *et al*. 2014a, Palermo *et al*. 2014b), the lateral resisting system must be conceived in order to be very flexible in terms of its stiffness, strength and ductility. In the recent years, research has been focused on enhanced bracing systems: at University of Toronto, Gray and his co-worker developed an hysteretic damper device, namely the Scorpion connectors which are nowadays produced by the Cast Connex (Gray *et al*. 2010); at University of Bologna Trombetti and his co-workers developed a so called Crescent Shaped Brace (CSB) device (Palermo *et al*. 2014a, Palermo *et al*. 2014b). The latter, thanks to its peculiar shape, allow design its lateral stiffness independently from its initial yield strength thus appearing suitable to be used for an enhanced lateral resisting system. Up to know studies on the CBS were mainly theoretical and aimed at obtaining analytical predictions of the force-displacement response of such devise.

In the present paper, the results of the first experimental tests performed on scaled prototypes are presented and compared with analytical and numerical predictions.

2 THE CRESCENT SHAPED BRACES

The Crescent Shaped Brace is an hysteretic device composed of two straight steel members which are connected with a specific angle to be used as diagonal bracings in framed structures (see figure 1). The “boomerang” shape of the CSB allows the practical designer to choose its lateral stiffness independently from its yield strength. Design formulas in order to get a configuration leading to a specific lateral stiffness and yield strength have been proposed in (Palermo *et al*. 2014a), while a design procedure explaining how to use CSBs to realize a controlled “shock absorbing soft story” according to the original idea by Fintel and Khan at the late 1960s (Fintel and Khan 1968) has been presented in (Palermo *et al*. 2014b).

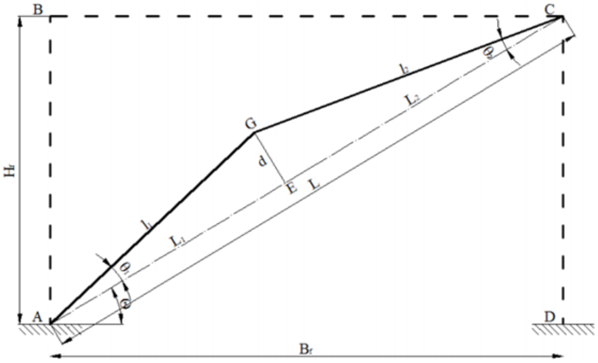

Figure 1: The geometry of a Crescent Shaped Brace (CSB) inserted in a frame.

3 THE EXPERIMENTAL TESTS

3.1 Description of the Tests and Specimens

The first experimental tests on CSB specimens were conducted in the laboratory of the University of Bologna, Italy, using a universal tensile machine METRO COM with a nominal capacity of up to 600 kN. The machine allows adjusting the test conditions varying both the load, through the pressure of the fluid, and the speed, through a flow regulator. The instrumentation is supplemented by a system of acquisition and processing of data (see figure 2). Three full rectangular specimens (cross section 41x15 mm^2), with a length “L” of about 100 cm and arm “d” equal to about 10 cm (1/10 of the length) were tested, namely R1, R2 and R3. Table 1 provides the main geometrical and mechanical characteristics of the tested specimens. The specimens are 1/6 scaled, representative of a brace inserted in a mirror frame of 3 m (height) x 6 m (span).

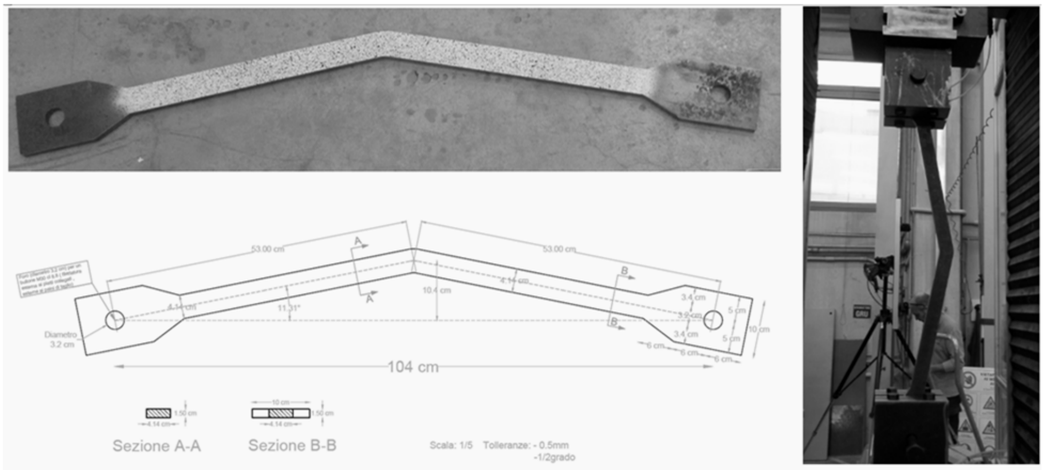

Figure 2. Upper left: specimen before test; Lower left: specimen dimensions; Right: set up of a specimen.

Table 1: Geometrical and mechanical properties of the specimens.

Specimen name	Section Type	Dimensions [mm]	Arm [mm]	Length [mm]	Angle [°]	Material
R1	Full Rectangular	41.4 x 15.0	104	1040	11.31	S275JR
R2	Full Rectangular	42.8 x 15.7	104	1040	11.31	S275JR
R3	Full Rectangular	42.5 x 15.8	104	1040	11.31	S275JR

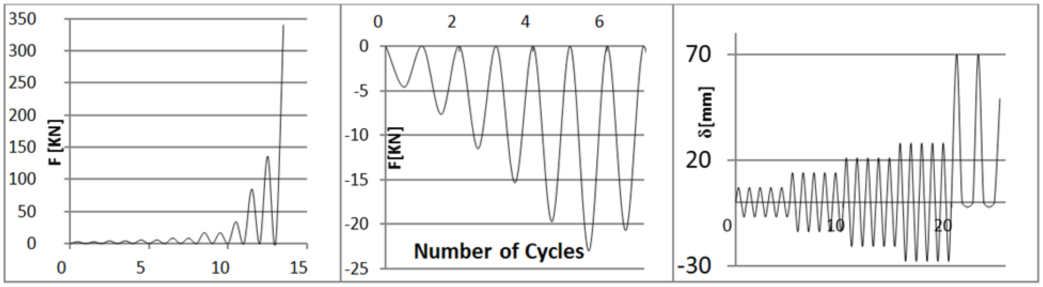

Figure 3: left) tensile test protocol; middle) compression test protocol; right) reversed cycle test protocol.

R1 has been subjected to cyclic tensile loads, R2 has been subjected to cyclic compression loads (followed by a monotonic load in tension up to the failure), while R3 has been subjected to reversed cyclic loads. The load protocol of each test is displayed in Figure 3.

3.2 Main Experimental Results

The experimental force-displacement responses of the three specimens are displayed in Figure 4. A summary of the main experimental results in terms of initial stiffness, yield strength and ultimate strength is given in Table 2.

Table 2: Experimental results in terms of stiffness, strength and displacement.

Specimen name	**Initial Stiffness K [KN/mm]**	**F_y [KN]**	**δ_y [mm]**	**F_u [KN]**	**δ_u [mm]**
R1	5	17	4	325	76
R2	5	23	9	302	65
R3	5	21	7	326	79

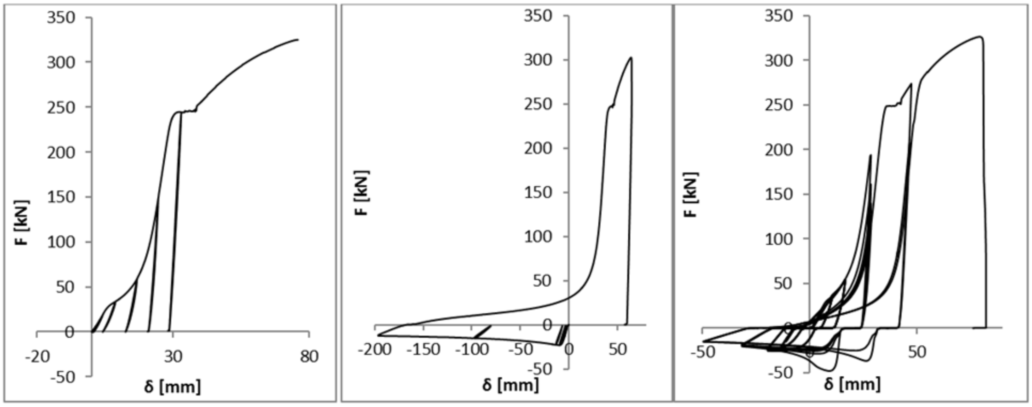

Figure 4: left) Experimental results of R1 under cyclic tensile loads; Middle) Experimental Results of R2 under cyclic compression test and tensile loads; Right) Experimental results of R3 under reversed cyclic loads.

R1 specimen evidenced the first yielding of the knee section around 17 KN, while the rupture happened for a lateral force equal to 325 KN with a total deformation of 76 mm. R2 specimen showed the peak at 23 kN with a lateral displacement of 9 mm. No rupture in compression was observed (the load is applied quasi-statically). The rupture was reached during the last cycle in tension for an ultimate load of 306 kN. R3 experienced an ultimate load of 326 kN with a lateral displacement of 78 mm.

4 EXPERIMENTAL RESULTS VS. ANALYTICAL PREDICTIONS

4.1 Response Under Tensile Loads

Let us consider a CSB device subject to a lateral force F. By Imposing the equilibrium in the deformed configuration (non-linear static) and assuming linear elastic constitutive behavior the following analytical lateral force-displacement response can be obtained:

$$\delta' = 2 \cdot \left(\frac{F \cdot L_1^3 \cdot \left(\sin \theta_1^{'}\right)^2}{3 \cdot E \cdot J} + \frac{F \cdot L_1 \cdot \left(\cos \theta_1^{'}\right)^2}{E \cdot A} + \frac{F \cdot L_1 \cdot \left(\sin \theta_1^{'}\right)^2}{G \cdot A} \right) \tag{1}$$

$$\delta' = 2 \cdot L_1 \cdot \cos(\theta_1^{'}) - 2 \cdot L_1 \cdot \cos(\theta_1) \tag{2}$$

After the first yielding $\delta'' = \delta_{y,flex}$ is achieved the constitutive law of the steel is assumed as elastic-perfectly plastic. Each straight portion of the CSB is modeled as: (i) an elastic part of length ηL_1, with a stiffness corresponding to the initial inertia; (ii) an elastic part of length $L_1 - \eta L_1$, with a reduced inertia J (varying with F) accounting for a partial plasticization of the knee section. The increase in the lateral displacement $\Delta\delta''$ after the first yielding is given by Eq (3).

$$\Delta\delta'' = \frac{\Delta F \cdot L_1^3 \cdot \left(\sin \theta_1^{''}\right)^2}{3 \cdot E \cdot J} + \frac{\Delta F \cdot L_1^3 \cdot \left(\sin \theta_1^{''}\right)^2}{3 \cdot E \cdot \tilde{J}} + 2 \cdot \frac{\Delta F \cdot L_1 \cdot \left(\cos \theta_1^{''}\right)^2}{E \cdot A} + 2 \cdot \frac{\Delta F \cdot L_1 \cdot \left(\sin \theta_1^{''}\right)^2}{G \cdot A} = \delta^{'} \tag{3}$$

4.2 Response Under Compression Loads

The force-displacement response of the CBS under compression loads (after the first yielding) has been studied by imposing the internal and external equilibrium in the deformed configuration. The internal equilibrium is shown by Eq. (4) and Eq. (5), while the external equilibrium is shown by Eq. (6) and Eq. (7).

$$N = 2 \cdot f_y \cdot b \cdot \overline{y} \tag{4}$$

$$M = f_y \cdot b \cdot \left(\frac{h^2}{4} - \overline{y}^2 \right) \tag{5}$$

$$N = \frac{4 \cdot K}{L^*} \cdot \left(\frac{\theta_1^{'} - \theta_1}{\sin \theta_1^{'}} \right) \tag{6}$$

$$M = N \cdot \frac{L^*}{2} \cdot \sin \theta_1^{'} \tag{7}$$

The system is modeled as an equivalent discrete system with two rigid members connected by a rotational spring in the knee section of stiffness K. Equalizing Eq (4), Eq (5), Eq (6) and Eq (7), the peak point (F_p, δ_p) can be obtained. After that, the softening branch is obtained by imposing the equilibrium in the deformed configuration (similarly as done for the case of tensile loads).

4.3 Experimental Envelope vs. Analytical Response

The envelope curves as obtained from each experimental test are compared with the analytical force-displacement response. It can be noted that the envelope response in compression is quite accurately reproduced. The envelope response in tension is well reproduced up a certain level of plasticization. Then the analytical response is stiffer, meaning the need of a more accurate description of the behavior for large deformations (see Figure 5).

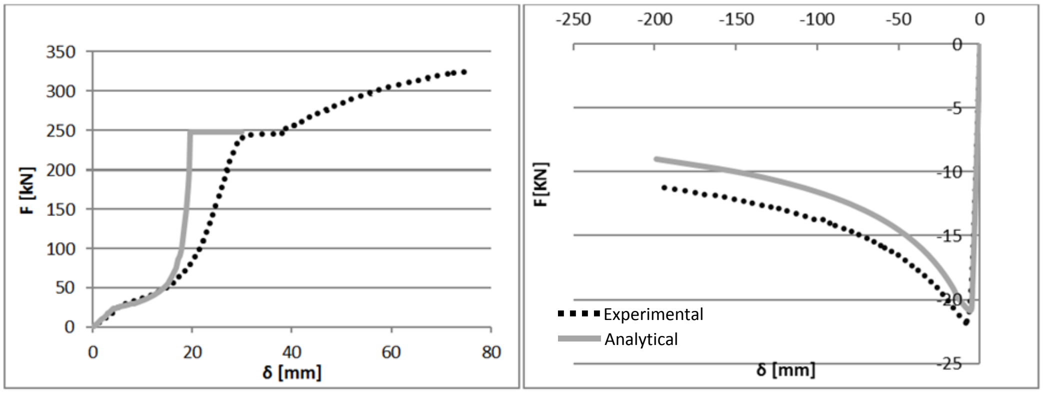

Figure 5. Experimental vs Analytical envelope response; Left: tension; Right: compression.

5 CONCLUSIONS

This paper presents the first results of experimental tests conducted on a special dissipative brace, referred to as Crescent Shaped Brace, together with simplified analytical models to capture the main futures of the experimental response, i.e. the stiffness, yield strength and inelastic response. The new hysteretic device has a boomerang geometric shape allowing sizing independently the lateral stiffness from the first yield strength. The results of the first experimental tests have, in essence, confirmed the effectiveness of the simplified analytical models. Prospectively, the next experimental investigations will be devoted to asses' specific effects such as local buckling and the influence of different cross sections, on both the global and local behavior.

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