INDIVIDUAL TESTING OF DISSIPATIVE BUCKLING RESTRAINED BRACES

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ABSTRACT

This work presents the results of experiments on four prototype buckling restrained braces. The devices were designed and built by the authors; consist basically of a steel cylinder as dissipative core and a steel tube filled with mortar as buckling restrainer casing. The design and production issues are accounted for in an integrated way and all the adopted technical solutions are fully explained. The experiments consist of imposing to the prototype devices axial cycling strain up to failure. The results of the tests are deeply described and discussed. The main conclusion of this work is that it is possible to obtain a reasonably cheap, efficient, robust, low maintenance and durable prototype device requiring only a low-tech production process.

KEYWORDS: Energy dissipators, Buckling restrained braces, Passive control, Testing, Fatigue life.

1. INTRODUCTION

Energy dissipators are a convenient option for earthquake-resistant design of buildings and other civil engineering constructions since they absorb most of the input energy thus protecting the main structure from damage even under strong seismic motions. Several types of devices have been proposed; those based on plastification of metals are simple, cheap and reliable while have shown repeatedly their usefulness. Among them, the buckling restrained braces are one of the dissipators more used for seismic protection of building frames. Consist of slender steel bars connected usually to the frame to be protected either like concentric diagonal braces or like chevron braces. Under horizontal seismic motions, the interstory drifts generate axial strains in such steel bars beyond their yielding points; their tension-compression cycles constitute the hysteresis loops. The buckling of these bars is prevented by embedding them in a stockiest encasing. Such encasing is usually formed by steel elements filled with mortar. Some sliding interface between the steel core and the surrounding mortar is required to prevent excessive shear stress transfer since it would reduce the longitudinal stress in the core thus impairing the energy dissipation. The buckling restrained braces posses several relevant advantages compared to other hysteretic devices:

- The ratio dissipated energy / added material is the highest in the comparative devices [Palazzo & Crisafulli, 2004]; the added material includes dissipators, bracing and connections. The degree of plastification is uniform along the whole body of the core.
- These dissipators constitute themselves a bracing system and no additional braces are required to connect each device to the main frame.
- A relevant experience is available since a number of individual and subassemblage tests have been carried out [Black, Makris & Aiken, 2004; Usami, Kasai & Kato 2003; Lopez et al. 2004;

Nishimoto et al. 2004; Tsai et al. 2004; Wada & Nakashima, 2004; Lee & Brunneau, 2005; Newell, Uang & Benzoni, 2006] and many realizations have been reported, mostly in Japan [Iwata 2004], Taiwan [Tsai et al. 2004], Canada [Tremblay, Degrange & Blouin, 1999] and the United States [Black, Makris, & Aiken, 2004]. Preliminary versions of design codes have been proposed [Kasai & Kibayashi, 2004; Kibayashi et al., 2004; Sabelli & Aiken, 2004,] and many references about design procedures are available [Wada & Nakashima 2004; Sabelli et al. 2005].

- Since the dissipative part of the device can encompass near the whole length of the brace, the required strain is rather low. Therefore, the plastic excursion is moderate, possibly providing high fatigue resistance.

In spite of the relevant existent background about the buckling restrained braces, there are still some open questions which require further research:

- **Design and production**. In spite that a number of devices are commercially available, no full details about them have been reported. In particular, the solutions for the sliding interface have been reported only scarcely [Tsai et al. 2004; Wada & Nakashima, 2004]. As well, most of the production issues have not been deeply discussed.
- **Experiments**. There is a certain lack of extensive fatigue testing aiming to report about the energy dissipation capacity of the device.
- **Buckling analysis**. The buckling design of the casing is based usually in simple models. Since some of the parameters are selected empirically, only over-conservative designs are feasible.
- **Structural behavior**. The structural behavior of the device is complicated because of the coexistence of several coupled issues: (i) joint behavior of three materials (inner and outer steel, mortar and the sliding interface), (ii) plastic cyclic behavior of the core, (iii) partial sliding between the core and the encasing mortar and (iv) large strains and displacements. A reliable and accurate numerical model considering these issues has not been reported. This lack prevents the proposal of innovative and daring solutions.
- **Effectiveness**. A comprehensive study about the seismic efficiency of these devices for a wide selection of buildings undergoing a broad range of earthquake inputs has not been reported.

This work addresses mainly the first two issues. Research focusing on the last three issues is in progress. The research approach consists basically of designing, producing and testing a number of short length dissipators [Palazzo et al. 2006; Palazzo et al. 2008] and taking advantage of the gained experience to better designing, producing and testing some bigger scale prototype devices; this paper concentrates on this last stage. A description of the research follows; such description is organized according to the aforementioned two issues.

- **Design and production**. A new type of buckling restrained brace is designed and a number of prototypes are produced; such device is rather similar to the existing ones. Main concerns of the design are: (i) efficient, simple, robust, low maintenance and durable device, (ii) low cost, (iii) simple manufacturing and (iv) rather easy to find materials.
- **Experiments**. Individual testing has been carried out in the University of Girona, Spain; the experiments consist of cycling axial loading until failure. Pseudo dynamic tests on devices installed on concrete frames are in progress.

This work belongs to a larger research project whose main objective is to promote the mass use of energy dissipators for seismic protection of buildings in seismic-prone regions. Particular attention is paid to developing countries.

2. DESIGN AND PRODUCTION

Beyond efficiency, the following qualities are sought in the proposed devices:

- **Simplicity**. The device should be robust, durable and virtually maintenance-free.
- **Low cost**. It should be kept on mind that the use of energy dissipators has to compete with other solutions and that in developing countries the economical issues are crucial.
- **Easy production**. Neither protected nor complex technologies are acceptable; in particular, neither big production facilities nor highly skilled and experienced workers should be required and the manufacturing should be fast. Moreover, the product has to be robust with respect to manufacturing errors. Any developing country should be able to produce the devices by itself.
- **Basic materials**. Only materials that are easy-to-find, replaceable and widely spread should be used. In particular, no particular requirements about the steel of the core are suitable.

The considered dissipator consists basically of a slender solid bar (cylinder) as dissipative steel core and a round thin-wall steel tube filled with high strength mortar (without shrinkage) as casing buckling restrainer. Two two-halved steel connectors are placed at both ends to ensure a proper anchoring to the frame. Figure 1 shows a plan view of the full device, an elevation of one of the ends and two front views; one of such front views includes a steel connector while the second one does not show it. Figure 2 shows some images of a particular device. Figure 2(a) and Figure 2(b) displays side and front views of one of the ends, respectively; the steel connectors are not incorporated. Figure 2(c) contains two pictures of a connector and Figure 2(d) shows their two halves.

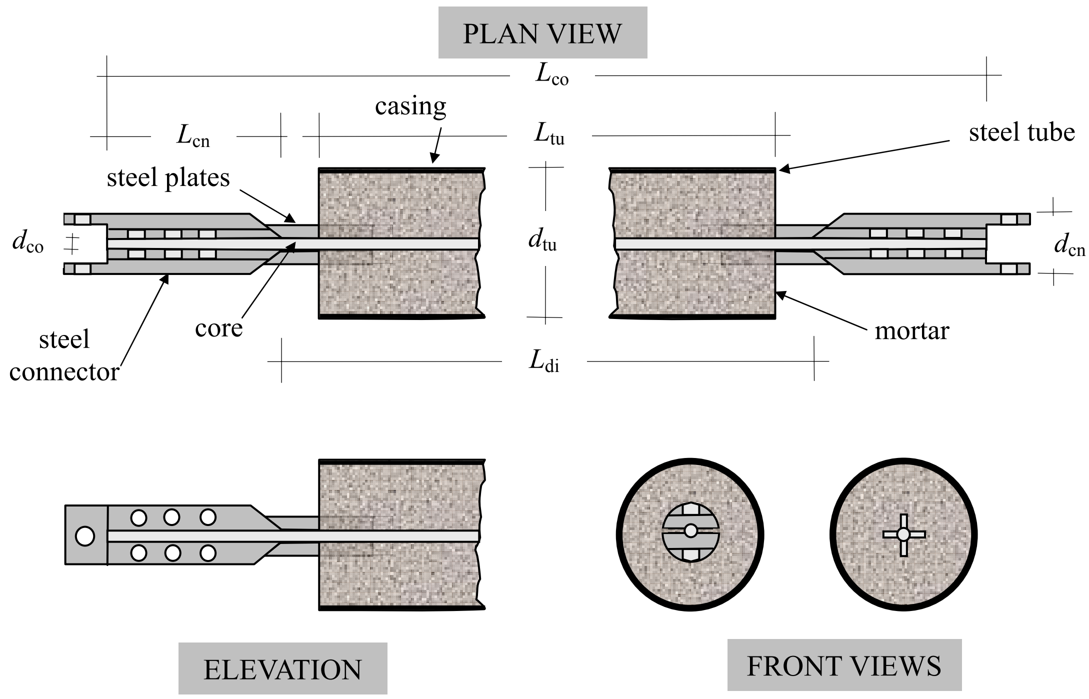
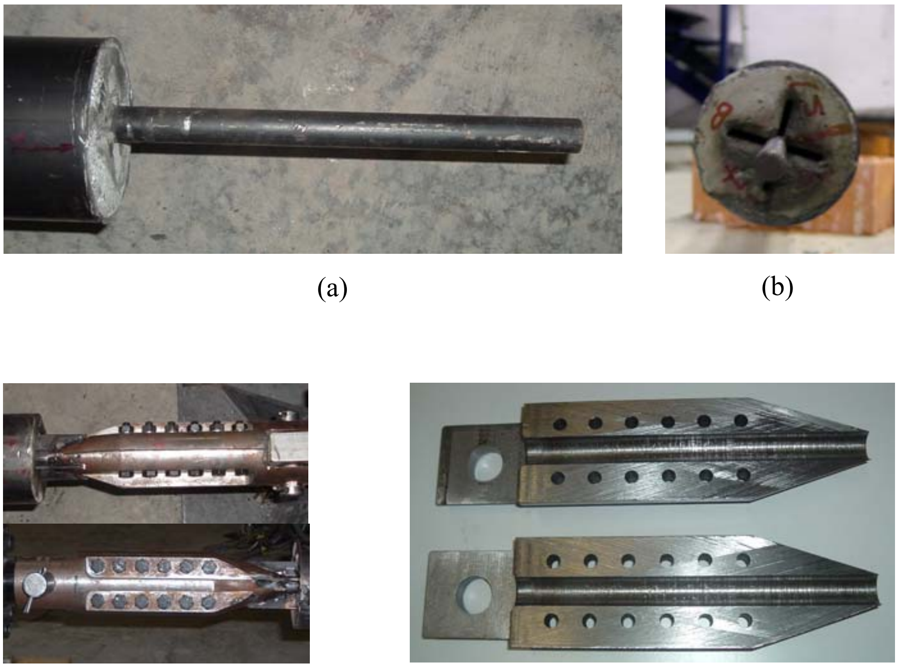


Figure 1. Considered prototype of a buckling restrained brace

Figure 1 and Figure 2 show that the two end steel connectors consist of two mirror halves; they are milled from a solid cylinder. The connection is based mainly on friction through prestressed bolts; since welding can impair the fatigue strength, is only used in the outer parts, where most of the stress has been transferred from the core to the connectors. When the core is tensioned and reaches its maximum extension their ends protrude beyond the protection of the casing; when the motion reverts, the core is compressed and both naked ends are in serious risk of buckling. To prevent this, four trapezoidal steel plates (see Figure 1 and Figure 2(c)) are welded to each of the connectors; they slide in cruciform-shaped grooves carved in the mortar, as shown by the right Front View in Figure 1 and by Figure 2(b).



(a) (b) (c) (d)

Figure 2. Pictures of a prototype of a buckling restrained brace

Table 1. Main geometrical parameters of prototypes D1, D2, D3 and D4

Devices	L_{co} (mm)	L_{cn} (mm)	L_{tu} (mm)	L_{di} (mm)	d_{co} (mm)	d_{tu} (mm)	t_{tu} (mm)	d_{cn} (mm)
D1 & D2	2808	200	2422	2466	10	90	3	80
D3 & D4	2808	270	2152	2196	22	115	3	85

The core can be made of ordinary construction steel. It is well known that the surface evenness reduces the risk of crack propagation and provides higher fatigue strength; however, for the sake of simplicity and of moderate cost none surface treatment is required. A key issue of the design is to ensure a proper sliding between the core and the surrounding mortar to avoid relevant shear stress transfer. In the proposed device, the sliding is ensured by a three-layer interface: the steel core is coated with Teflon®, lubricated with grease and wrapped with rubber. The Teflon is selected because of its high strength and low friction coefficient. The purposes of the rubber are: to provide further shear flexibility, to guarantee an even sliding surface and to allow the transversal expansion of the core when compressed. The width of the rubber layer is 17 mm. Four prototypes (termed D1, D2, D3 ad D4) have been produced according to the described technology (see Figure 1). The total length of the devices is limited to 3 m because of restrictions in the testing laboratory. The values of the geometrical parameters (Figure 1) are summarized in Table 1.

Table 1 shows that dissipators D1 and D2, as well as D3 and D4 are designed alike to compare their results. For all the devices the difference between the length of the dissipative segment of the core L_{di} and the length of the tube L_{tu} is 44 mm (22 mm each side); it is intended to allow the slide of the core with respect the tube. This value is about six times the yielding displacement; hence, this design largely allows ductility ratios slightly above 5. The diameter of the core of devices D3 and D4 corresponds to usual design values for lower floors in mid-to-tall buildings; the one of devices D1 and D2 corresponds either to upper floors or to short buildings. The restraining casing has been designed from the approach suggested by [Black, Makris and Aiken, 2004]. For both the tube and the core, ordinary construction steel has been used; its yielding point is f_y = 275 MPa while the ultimate strength is f_u = 410 MPa. Commercially available mortar without shrinkage has been used; the expectable compressive strength ranges between 45 and 50 MPa.

A deeper description of the design and production issues is available in [Palazzo et al. 2008].

3. GENERAL DESCRIPTION OF THE EXPERIMENTS

The four prototypes were tested in the University of Girona, Spain. The experiments are individual (i.e. there are no subassemblages accounting for the frame) and consist of imposing cycling axial deformation until failure. A comprehensive description is available in [Palazzo et al. 2008]. The objectives are (i) to assess the performance of the proposed devices, (ii) to learn deeply about their structural behavior, (iii) to characterize their hysteretic behavior and (iv) to obtain results useful to calibrate numerical models to be developed. The experiments are designed to reach these goals.

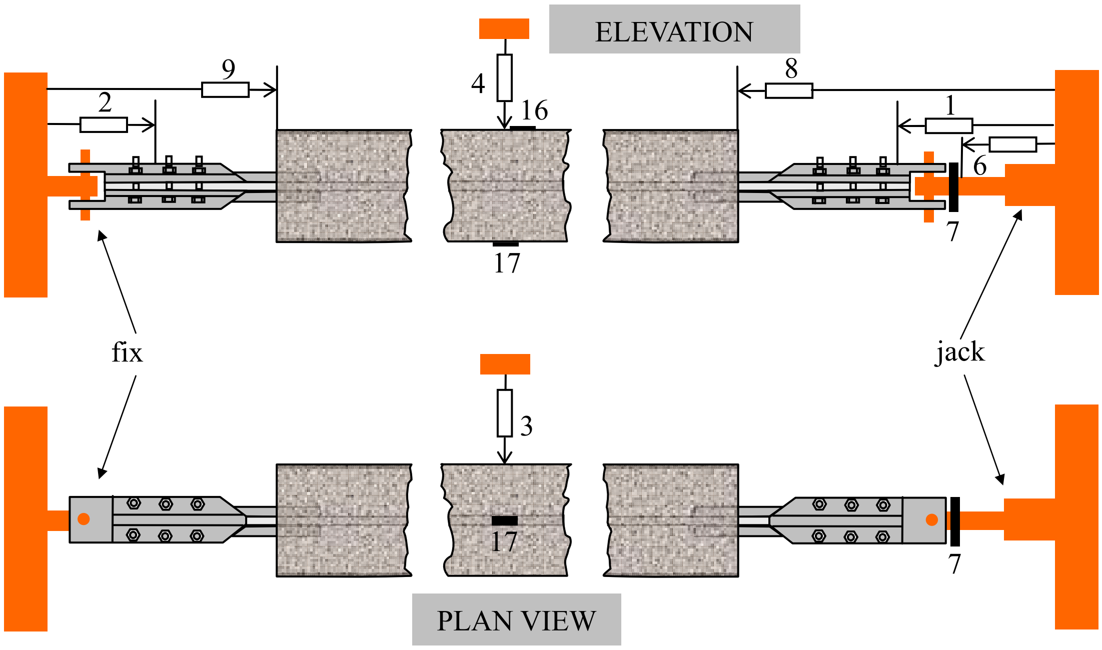


Figure 3. Testing rig for dissipators D1, D2, D3 and D4

4. TESTING RIG

Dissipators D1, D2, D3 and D4 were placed horizontally fixed by one of their ends and connected by the other end to a servo-controlled hydraulic jack. Figure 3 displays two sketches (plan view and elevation) while Figure 4 shows a picture of the testing rig of dissipator D1. Figure 3 and Figure 4 show that the registered magnitudes are: axial force in the jack (sensor 7), displacement of the actuator (sensor 6), longitudinal displacements of the steel connectors (sensors 2 and 1), longitudinal displacements of the end sections of the tube (sensors 8 and 9), transversal horizontal and vertical displacements of the mid section of the tube (sensors 3 and 4, respectively) and axial strains of the tube (sensors 16 and 17). At dissipator D1, two additional strain gauges were fixed near the end sections of the tube (sensors 18 and 19). Gauges 16 and 17 were placed at opposite ends of a horizontal diameter of the mid section to obtain the axial forces and the horizontal bending moments.

The imposed displacements consisted two consecutive phases: growing-amplitude cycles and constant-amplitude cycles until failure; in the second phase the semi-amplitude is 5 Δ_y, Δ_y being the yielding displacement. This amplitude is selected as a common demand for these devices under strong seismic inputs. These loading histories are intended to evaluate the energy dissipation capacity under constant ductility demand.

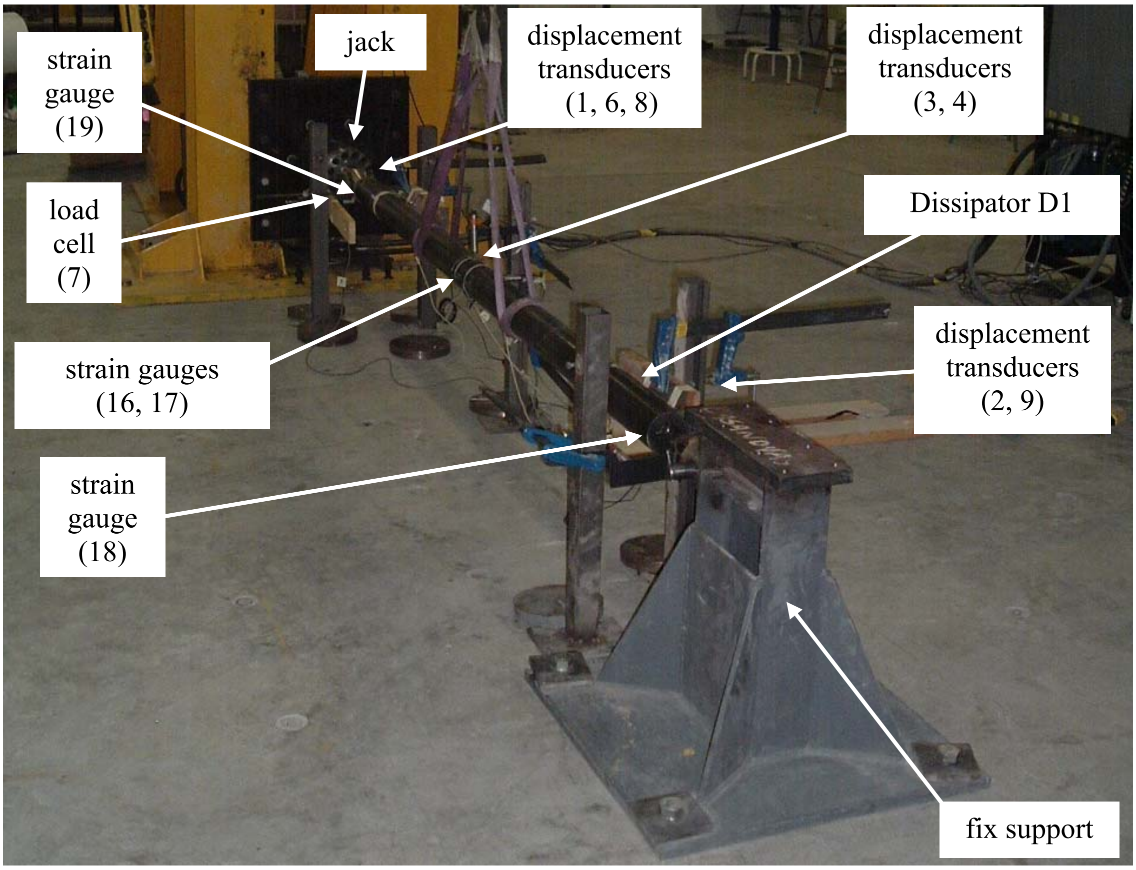


Figure 4. Testing rig for dissipator D1

5. TESTING RESULTS

The tests were conducted without major problems. The main incident was a premature failure of dissipator D4 by local buckling of the naked core ends as the trapezoidal steel plates were not rigid enough; to avoid this, in the device D3, two sliding supports were added near the end connections to prevent the lateral displacements of the tube. As well, the rotation capacity of the two pinned connections (Figure 3) proved to be damaging for the behavior of the dissipator D1 as relevant rotations were observed; the situation for dissipators D2, D3 and D4 was improved by inserting steel wedges and can sheets that transformed the hinged connections in near-clamped ones.

Figure 5 displays hysteresis loops for dissipator D2. Positive values of force correspond to tension and of displacement to elongation. The first and last irregular loops have been eliminated. To facilitate the interpretation an ideal bilinear hysteresis loop is also drawn in dashed lines.

The following trends can be observed from Figure 5:

- The hysteretic behavior is stable. The force amplitude decreases after the first cycles but tends to stabilize quite fast. This is due to a progressive detachment between the core and the surrounding mortar.
- Every time the force in the jack changes its sign, the plot exhibits a near horizontal jump due to the gap in the pin-joint connections between the dissipator and the end supports (see Figure 3).
- Even the core exhibits permanent buckling deformations, it does not affect the plots.

- The plastic tension loading branches are curved, yet tend to become flat horizontal. This can be also observed in the plastic compression loading branches but their end segments exhibit a rather sudden increase leading to a sharper peak and a reversal in the curvature of the branch. This fact is due to the higher mortar contribution (because of the rising of the friction forces) during the core buckling. This effect is rather unwelcome since it does not raise remarkably the dissipated energy while the increase of force is more relevant.

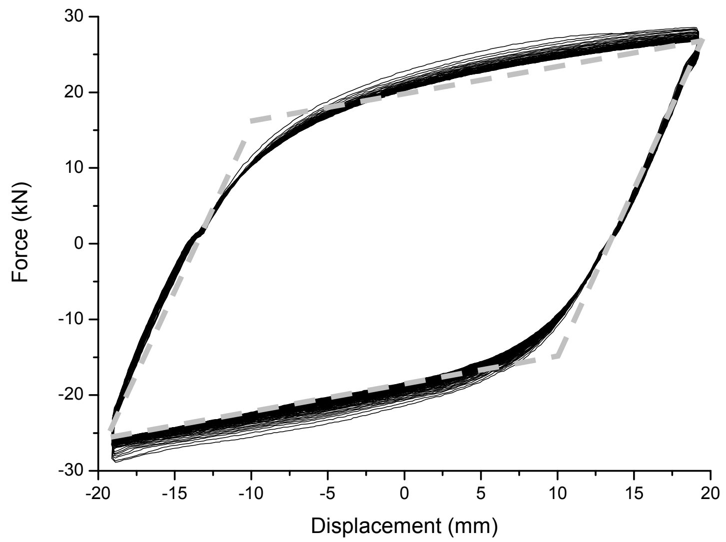


Figure 5. Regular hysteresis loops for dissipator D2 (channel 7 vs. channel 6)

The analysis of the results of the other devices provides similar conclusions [Palazzo et al. 2008].

Table 2 presents a summary of the results of tests for dissipators D1, D2, D3 and D4. The irregular values corresponding to behavior near or after failure are not accounted for. In Table 2, "Buckled Ends?" refers to the local buckling of the naked core ends. The dissipated energy is the area encompassed by the hysteresis loops normalized with respect to the elastic energy corresponding to the yielding displacement. The "Cumulative plastic ductility" [Black, Makris and Aiken, 2004] is a dimensionless normalized expression of the cumulative plastic deformation: $\Sigma|\Delta^+ - \Delta^-| / \Delta_y$ where Δ^+ and Δ^- are the maximum and minimum values of the plastic displacement, respectively. The sum is extended to all the plastic excursions.

Table 2. Main results of the tests of dissipators D1, D2, D3 and D4

Device	Buckled Ends?	No. of cycles	Dissipated energy	Cumulative plastic ductility
D1	NO	160	3492	2454
D2	NO	131	2928	1976
D3	NO	387	8856	6662
D4	YES	73	1485	1124

6. CONCLUSIONS

It is feasible to design buckling restrained braces that are efficient, robust, virtually maintenance-free, durable, reasonably cheap, easy to produce and made of basic and easily replaceable materials. The tests showed that the devices performed properly. It is remarkable that the inner observation of the tested devices showed that the mortar was not damaged.

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