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Experimental and analytical investigation on the behavior of metallic Box-Shaped Dampers (BSD)

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ABSTRACT

A Metallic Box-Shaped Damper (BSD) which is introduced here, is an effective energy dissipator device which is very simple and low-cost. BSD is a box made of several steel plates which is mounted along diagonal members of a braced frame. The lateral movement of the structure leads to the formation of plastic hinge in the damper. The function of this damper is far from complex, and its governing relationships are derived from basic mechanical equations. The validity of these relationships has been verified by performing both experimental tests and numerical analyses. The wide hysteresis curve and the presence of two levels of plastic energy dissipation enable it to withstand moderate and severe earthquakes. Unlike many existing seismic dampers, the stiffness and strength of the BSD device, are not interdependent parameters and the designer can choose the required stiffness while keeping the strength constant. The existence of customizable parameters such as steel type, overall dimensions of the box and also thickness of steel plates provides excellent ability for designers to obtain desirable behavior in terms of ultimate capacity, stiffness and energy dissipation, hence, implementing an adjustable fuse in structures. Also, selecting the appropriate design parameters can minimize the maximum plastic strain, which further increases the displacement capacity of BSD. In this research, four specimens of BSD investigated experimentally in two types. The results of this research show that the hysteresis plot of the BSD is wide and ductility factor is 19.3 and 11.2 in tension and compression, respectively.

1. Introduction

Ductility is one of the most important seismic design parameters which can be provided by creating limited damages in the structure. These damages can occur in all seismic resisting members of the structure. It is difficult to manage them, and after a severe earthquake, probably, there are too many damaged members or connections in the whole structure. On the other hand, ductility can be provided by special ductile elements, as a fuse or a damper. In recent decades, in addition to seismic isolators (e.g. elastomeric bearings and lead rubber bearings) [1,2], several types of energy dissipation systems have been developed to provide ductility or to increase energy dissipated in the structures., including: a) displacement-control systems (e.g. Metallic Yielding Damper [3,4], Friction device [5]), b) velocity-control systems (e.g. viscous and viscoelastic dampers [6–9]), c) motion-control systems (e.g. tuned mass and liquid dampers [10,11]) and d) Self-Centering Systems [12].

In recent decades, several types of metallic yielding damper have been introduced. The first researches on metallic dampers date back to the 1970 s [13,14]. Since then, various types of these dampers have been introduced, and in all of them, steel has been yielded into one of four axial, shear, torsional, or bending modes. The main advantages of the metallic dampers are their ability to increase ductility of the systems and hence concentrating the damages caused by earthquake in the damper rather than elements of structure. With replacement of the dampers, as a fuse, the structural system will be easily repaired.

Triangular-plate Added Damping And Stiffness (TADAS) devices include a few triangular steel plates which connect Chevron braces to the beams. The lateral movements impose flexural deformations in these plates. Therefore, yielding occurs concurrently over the full height of the plates. The response modification factor of this system is greater than the Special Moment Resisting Frame [15–19].

Knee Braced Frame (KBF) systems consist of a braced frame with diagonal braces connected to a ductile knee member. Yielding of the knees element dissipate energy during severe motions. Experimental results revealed that the maximum equivalent damping ratio of KBF systems can be more than 20% [20,21].

Buckling Restrained Brace, BRB, is made of a steel core enclosed in a steel or concrete casing. The core and casing are separated by unbonding materials. Plastic deformations and energy dissipation occur in

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core due to axial forces [22–25].

Steel Slit Damper, SSD, is made of a number of spaced plates. The location of this damper can be different in the structure. It can be installed in beam to column connections, used like a shear wall in the system or attach Chevron braces to the beams. Deformation at the two ends of the damper leads to flexural energy dissipation of the system [26–29]. Box-shaped steel slit damper is a new type of SSD that has been proposed recently. Researchers shown that this type of dampers which are made by adding four slit plates to internal and external box shape casings, have good ductility and energy dissipation capacity when used as knee braces [30].

Steel shear links, SL, which are I-shape devices made from hot laminated steel plates with different configurations, are another type of energy dissipative dampers which connect chevron braces to the main structure. The flanges of SL which represent stiffer parts, connects the device to structural element and the web dissipates energy through so called "dissipative windows" which have reduced thickness made by milling process. Experimental results showed suitability of these devices for design purpose [31].

Researchers also studied the behavior of U-shaped metallic-yielding damper which is made by cold bending mild steel strips. Lateral movements cause plastic deformations and dissipate energy in the damper. The circular arrangement of U elements allows using the energy dissipating capacity of the device in all directions, enabling the designer to use this damper in uniaxial or biaxial configuration [32].

Steel Ring as an energy dissipator, was first studied in 2008 by Kafi [33]. This energy dissipator device consists of a steel pipe or two half-rings that are mounted along the diagonal member of a braced frame. Studies showed that a brace equipped with the steel ring exhibit a stable and wide hysteresis curve while other members of the system stay in elastic regions [34–38].

Researchers also worked on a combination of different energy dissipation devices. For example, Hosseini Hashemi and Alirezaei studied EKF system both numerically and experimentally [39]. This system is a combination of Eccentrically Braced Frame (EBF) and Knee Braced Frame (KBF). There are two level fuses in EKF, the knee and the link elements and it can dissipate energy when the structure is subjected to moderate and severe lateral motions, respectively.

A box shaped element (BSD) is introduced here as a damper. It consists of four steel plates which formed a box, and two plates which are used for connection to brace member. The tensile and compressive forces of the brace create plastic bending deformations in the members of damper. These plastic deformations cause energy dissipation in the structure. The adjustable parameters of this damper (material type, length and thickness of the members) make it possible to determine the ultimate capacity, stiffness and energy dissipation, based on seismic demand. The small size of the BSD provides the ability to use it in the new configurations, e.g. Toggle Mechanism, Scissor-Jack. In this case, magnification factor is about 2–3 [40,41].

In this research, first, the behavior of proposed box-shaped damper has been investigated experimentally, in two types and four specimens. Then, the selected specimen studied by a numerical analysis. The behavior of BSD has been investigated analytically. The relationships obtained from the experiments and numerical studies were compared with those obtained analytically. Finally, the effects of design parameters on behavior of BSD have been studied.

2. Description of proposed BSD

The introduced damper, BSD (Box-Shaped Damper), is in the shape of a box made of ductile steel plates, Fig. 1. This damper is placed as a fuse along diagonal member of braced frame and it is meant to increase the ductility of the system and also prevent the buckling of the member, Fig. 1.

The main concept in the BSD is its simplicity, both in its behavior and production. The relationships of BSD are simply derived from the basic engineering sciences. No special materials or tools are needed to produce it. It is flexible and can be as effective as a fuse in designing and retrofitting structures.

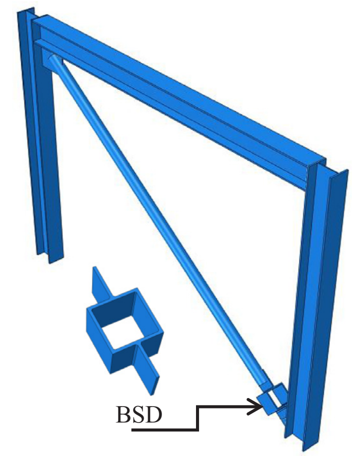

Fig. 1. Diagonally braced frame equipped with BSD system.

In most lateral resisting and passive supplemental damping systems, the strength and stiffness parameters are strongly correlated. As one increases or decreases, the other increases or decreases. For example, in the moment resisting or concentrically braced frames (MRF or CBF), the stiffness and strength increase as the size of frame member increases. In most current dampers, e.g. in TADAS, as the thickness of the plates increases, the stiffness and strength increase. But as it will be mentioned later, different types of Force-displacement plots can be obtained by adjusting the dimensions and thickness of plates in BSD. In these curves, unlike many tools of energy dissipations, stiffness and strength are not interdependent.

The existence of two adjustable yielding levels (depending on dimensions, thickness and property of steel member) in the force–displacement plot of the BSD allows us to easily design the required damper according to the seismic demands in cases of medium or severe earthquakes.

The governing equations of the BSD are virtually independent of the shape of steel parts, hence, when more load capacity is needed, any steel section like hot rolled shapes may be used to build the BSD.

BSD is consisted of three main parts, i.e. head plates (Plate h) with the length of L_h and thickness of t_h; left and right side plates (Plate v) with the length of L_v and thickness of t_v; and the connection plates (Plate c) with a thickness of t_c. All plates are connected with complete-joint-penetration (CJP) groove welds. The connection of plates c and h is made in two types: Type A, rigid connection by CJP groove welds with reinforcing fillet welds placed on both sides. Type B, pinned connection by two bars that bolted together, Fig. 2.

The axial force imposed by diagonal member of brace generates flexural deformations in the BSD elements. This force which is being transferred to BSD through plate c is either tensile or compressive, flexural deformations of BSD system are shown in Fig. 3.

3. Experimental studies

3.1. Specimens and loading

Four specimens were tested in two types of BSD. The specimens called S1, S2 and S3 (Type A) were tested under tensile, compressive and cyclic loading, respectively. The specimen S4 (Type B) were tested cyclic loading. A 12 mm plate is used to build the specimens which its geometrical dimensions are shown in Fig. 4. To connect the specimens to the actuator, two 24 mm holes were drilled in the upper and lower connection plates. All plates are connected with CJP groove welds. W1