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Evaluation of yielding shear panel device for passive energy dissipation

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ABSTRACT

The paper describes an experimental investigation of a new earthquake damper, the yielding shear panel device (YSPD), for civil structures. It utilizes energy dissipation through plastic shear deformation of a thin diaphragm steel plate welded inside a square hollow section (SHS). Its performance is verified by nineteen monotonic and cyclic tests. Experiments showed that certain specimens exhibited stable behavior and were capable of dissipating a significant amount of energy. The performance is influenced by the diaphragm plate slenderness and by the in-plane rigidity of the surrounding SHS. Slender plates undergo elastoplastic shear buckling and exhibit stable though slightly pinched hysteresis response. Stocky plates impose high deformation demand on the surrounding SHS that hinders their cyclic performance. The equivalent viscous damping offered by the test specimens, on their own, and the cumulative energy dissipation are quantified. Fabrication, implementation and replacement of the damper proved to be easy and inexpensive. The YSPD offers a potentially viable alternative for seismic retrofitting of existing frame structures.

1. Introduction

Interest in the development of passive energy dissipation in earthquake risk mitigation of civil structures has greatly increased in the last two decades. [1,2] During an earthquake, a large amount of energy is imparted to a structure. The traditional design approach relies on the energy dissipation as a consequence of inelastic deformation of particular structural zones. The permanent damage of the post-disaster structure is often so serious that it would be expensive to repair, if at all possible. The concept of passive energy dissipation, however, attempts to reduce such permanent damage to the structure. With designated energy dissipative devices installed within a structure, a portion of the input seismic energy could be diverted into these devices; as a result damage of the parent structure can be effectively reduced. The inclusion of dissipative devices in a structure is expected to alter its stiffness and damping and hence influence its structural response [3]. In addition, by strategically locating these devices, repair and/or replacement of the devices following an earthquake can be carried out with minimal interruption to occupancy, a crucial benefit to building owners and occupants.

A number of dissipative devices utilizing plastic deformation of metals have been proposed. Devices which make use of flexural deformation of metals include the patented ADAS [4], its variants TADAS [5] and Cu-ADAS [6] and the Steel Slit Damper (SSD) [7]. The Buckling-restrained brace (BRB) [8], on the other hand, makes use of the axial deformation of steel.

Devices such as the ADAS, SSD and the proposed YSPD are usually envisaged to be connected between the top of an inverted V-brace (chevron brace) system and a floor beam in a structural panel (Fig. 1). This results in the device being connected in series to the bracing system. The resultant in-plane lateral stiffness of the brace-device assembly k_{bd}, can be obtained from the individual stiffness of the brace, k_b, and the device, k_d,

$$k_{bd} = \frac{1}{\frac{1}{k_b} + \frac{1}{k_d}} = \frac{k_b k_d}{k_b + k_d}. \quad (1)$$

Eq. (1) indicates that the brace stiffness is compromised by the insertion of a flexible damper. If the brace stiffness is required to withstand in-service lateral loads, a relatively high device-to-brace stiffness is then necessary. Dampers which rely on plastic flexural deformation are generally flexible; hence multiple plates are used to build up the required stiffness.

On the other hand, the in-plane shear strength and stiffness of steel plates has been used by designers as a primary lateral load resistant system. The steel plate shear wall (SPSW) is one such application that has been used in Europe, North America and Japan. The SPSW provides high in-plane stiffness to resist lateral loads and represents an alternative to conventional reinforced concrete walls. Thin steel plates buckle elastically at a rather low level

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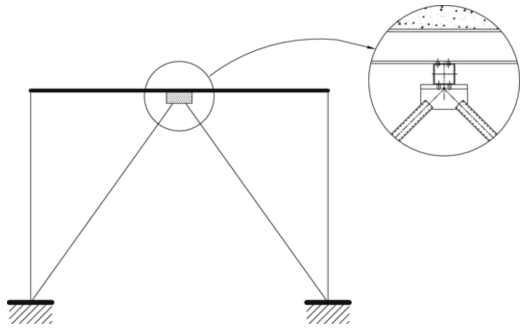

Fig. 1. Frame-brace-device assembly.

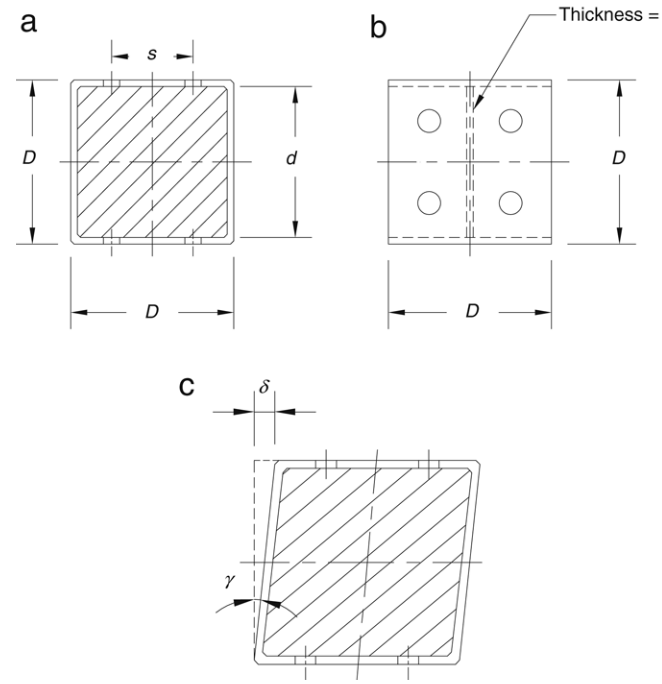

Fig. 2. Yielding shear panel device (YSPD) (a) Elevation (b) Top view (c) Deformed shape.

of shear stress; however plate buckling is not synonymous with failure if the plate is adequately supported along its boundaries. Basler [9] demonstrated that in the presence of tension field action, steel plates offer substantially higher strength and ductility than concrete walls. The cyclic behavior of steel plate shear wall panels has been investigated by a number of researchers [10–13].

Generally, a good metallic device for seismic applications must exhibit: (1) adequate elastic stiffness to withstand in-service lateral load (e.g. wind); (2) a yield strength of the damper exceeding the expected in-service lateral loads; (3) large energy dissipative capability; and (4) a stable hysteretic force–displacement response which can be modeled numerically.

To utilize the high in-plane stiffness and energy dissipative capability of shearing actions in steel plates, a new metallic damper, the Yielding Shear Panel Device (YSPD) has been proposed by Schmidt et al. [14] and further developed by Williams and Albermani [15]. They performed quasi-static tests on a half-scaled moment resisting frame equipped with a YSPD and showed that a considerable amount of energy was dissipated through the damper [15].

This paper concentrates on the performance of the YSPD itself (isolated from the parent frame structure). A series of sub-assemblage tests on half-scaled YSPD specimens is conducted. A specially designed test setup was developed for this purpose. A total of 19 tests were conducted using various plate slenderness and device configurations. These tests are presented and discussed in this paper. In addition a simple analytical design method of the device is presented together with a hysteretic model that can be calibrated using the obtained experimental results.

2. Yielding shear panel device (YSPD)

Figs. 2 and Fig. 8 show the yielding shear panel device tested in this research. It was fabricated using a short segment of a square hollow section (SHS, dimension $D \times DxT$) with a steel diaphragm plate (thickness t) welded inside it. The square section was chosen in this study since it was expected to be more effective than a rectangular section in developing 45 degree tension field.

The length of the SHS section was chosen to equal its width (i.e. D). The relative horizontal displacement between the top and bottom connections causes the diaphragm plate to deform in shear (Fig. 2(c)). When the displacement is sufficiently large the plate deforms plastically, and as a result input energy is dissipated. Fabrication and installation of the device is simple and inexpensive.

3. Preliminary design of YSPD

Assuming a minor contribution from SHS, the theoretical elastic in-plane lateral stiffness of the device k_d is given by,

$$k_d = Gtd/d = Gt \tag{2}$$

where G is shear modulus and t is the thickness of the diaphragm plate. For a compact diaphragm plate the yield strength can be taken as the shear yield strength (assuming a von Mises yield criterion);

$$F_y = \frac{f_y}{\sqrt{3}} td \tag{3}$$

where d is the width of steel plate and f_y is its tensile yield stress. Consequently, the yield displacement of the device is,

$$u_y = \frac{F_y}{k_d} = \frac{f_y d}{\sqrt{3}G}. \tag{4}$$

For a device with a slender diaphragm plate, elastic shear buckling will take place. The critical shear stress for a simply supported plate is given by,

$$\tau_{cr} = k_s \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{d}\right)^2 \tag{5}$$

where k_s depends on the aspect ratio of the plate, and equals 9.35 for square plates. E and ν are Young's modulus and Poisson's ratio respectively. Taking $\nu = 0.3$ and $E = 205$ GPa, the limiting plate slenderness ratio at which buckling occurs is

$$d/t = 1732/\sqrt{f_y} \tag{6}$$

where f_y is the tensile yield strength of the diaphragm plate (MPa).

4. Test program

Performance of passive energy devices is often influenced by factors such as connection details, the surrounding SHS and possible fabrication flaws. Therefore, it is essential to conduct a testing program to verify the cyclic performance and energy dissipation capacity of the proposed YSPD.

4.1. Specimens

Twelve specimens similar to Fig. 2 were fabricated at the structures laboratory of the City University of Hong Kong. Two different SHS sections (100 × 100 × 4 and 120 × 120 × 5) and three diaphragm plate thicknesses (2, 3, and 4 mm) were used, resulting