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Quasi-static test of assembled steel shear panel dampers with optimized shapes

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ABSTRACT

A metallic shear panel damper with the shape optimized by stress contour lines is proposed in this study to mitigate stress concentration, reduce the effect of hot welds, and improve energy consumption efficiency. The stress contour line is defined according to the J2 plasticity theory, and the optimized shape is obtained by assuming that the points on the same contour line yield simultaneously. Different optimized shapes are developed considering various loading conditions. The design formulas for the stiffness and the strength are then derived, and further examined by nine dampers tested quasi-statically. Four are tested laterally under the vertical axial load to simulate real boundary conditions. All dampers can be easily installed or replaced because of the all-bolt connections. The test results demonstrate that the proposed metallic shear damper has a stable energy-dissipation capacity and a better low-cycle fatigue capability than traditional shear dampers without shape optimization. The stiffness and strength design values match the test values very well. The axial deformation in the specimen has been observed and identified due to the interaction among the cyclic axial-shear coupled plasticity, the geometric nonlinearity, and the higher lateral buckling modes. Compared with the non-optimized damper, the distribution of plastic deformation in the proposed dampers is more uniform, and the stress concentration is reduced significantly.

1. Introduction

Traditional building structures consume seismic energy through the plasticity of structural components, resulting in extensive damage within these components. Although this can protect human life, the difficulty of repairing these components can lead to enormous economic losses [1]. Enhanced building performance and resilience are required in modern societies, so human activity is not interrupted or can be quickly restored after strong earthquakes. Installing passive dampers to dissipate the seismic energy is an effective method, in which the main gravity-bearing structural components remain almost elastic. Various types of dampers have been developed and applied in the past decades, such as displacement dependent buckling restrained braces (BRB), metallic shear panel dampers, friction-based Pall dampers, and velocity dependent viscous and viscoelastic dampers [2]. Of these, metallic dampers are found to be most economic and have a stable and large capacity to dissipate seismic energy.

Kelly et al. [3] put forward the steel shear panel damper in 1972, which has since been widely used because of its simple configuration, clear mechanical mechanism, and excellent low cycle fatigue features. The damper consists of flanges, stiffeners, steel shear panels to consume energy, and end plates connecting to the main building structure. All components are welded together. In subsequent research [4–7] it was observed that the steel shear panels buckled and the welds fractured due to the significant stress concentration and the plastic strain accumulation, particularly in the regions most affected by the weld heat. To increase the energy dissipation, some studies have developed some metallic panel dampers with special shapes. Chan et al. [8] conducted experimental research for the Steel Slit Damper (SSD), which was fabricated using a wide-flange steel with a number of slits on the web, and a larger energy dissipation capacity can be achieved. Yong et al. [9] studied the cyclic behavior of non-uniform steel strip dampers, such as dumb bell-shaped strip and a tapered strip. Such configurations can avoid both brittle failure and excessive force to the primary structure. Fairs et al. [10] investigated a metallic energy dissipater called Perforated Yielding Shear Panel Device (PYSPD), which comprised of a thin perforated diaphragm plate welded inside a short length square hollow section. The perforations reduced the elastic stiffness and yield strength, while increased the plastic areas to consume energy. Yong et al. [11] improved the conventional slit damper by use of an hourglass-shaped strip. It has been found the plastic bending moment reached at all cross sections simultaneously. Valizadeh et al. [12]

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opened some holes with different dimensions on a steel plate shear wall to improve the ductile and energy absorption capacity. Other studies [13–18] have focused on the deployment and design of stiffeners to solve the premature fracture problem, but the effectiveness is in general limited.

To solve this problem, the panel shape is often optimized to enlarge the plastification area and the stress concentration can then be mitigated. Zhang et al. [19] improved the low cycle fatigue performance of steel shear panel dampers by weakening the thickness in the center area of the energy dissipater. Liu et al. [20] used an arc shape at four corners and a rectangular middle panel. Quasi-static tests demonstrated that the ultimate bearing capacity was constant while the ultimate shear angle increased by 44%. In subsequent studies [21], a parabolic shape was used for the shear panel damper as a local optimization, and a numerical study indicated that the maximum accumulative plastic strain was reduced by 82.2% while the total energy consumption was only reduced by 2.3%. A globally optimal solution for the panel shape was obtained by Deng et al. [22,23] with a simulated annealing algorithm. Both numerical and experimental results revealed that the maximum accumulative plastic strain was reduced by 70%.

A new type of steel shear panel damper is proposed in this study, with the shape optimized by stress contour lines considering different loading patterns. All components of the damper are assembled using high-strength bolts for convenient installation or replacement. Design formulas for the stiffness and strength are then developed for the engineering application. Finally, the effectiveness of the shape-optimized damper and the correctness of the design formulas are demonstrated through the testing of nine specimens. The influence of the vertical axial load on the lateral bearing force is also examined.

2. Configuration of assembled steel shear panel dampers

This new type of assembled steel shear panel damper (ASSD) consists of one energy dissipater, two L-shaped connectors, two buckling restrainers, and two pieces of partition plates. These are assembled using friction type high-strength bolts, as shown in Fig. 1(a), which both reduce the adverse effect of welding heat and can be conveniently installed or replaced after severe earthquakes. The energy dissipater with effectiveness height h and width b, as shown in Fig. 1(b), deforms laterally in the plane. The surface of the panel has two treatments: first, the two shadow regions are treated by sand-blasting to increase the friction force when clamped by the L-shaped connectors and the buckling restrainers; and second the rest area is deformed to dissipate the seismic energy and galvanized to protect it from rust. The deformation area can be designed with a special shape to maximize the energy dissipation capacity, which is defined by the profile function $f(x)$. The clamped areas are designed elastically in any case. Note that all corners are chamfered and rounded to avoid stress concentration. The L-shaped connectors clamp the energy dissipater tightly through the high-strength friction-type bolts, and are connected to the main structural components securely also by another set of high-strength bolts. The buckling restrainers serve as the confinement to avoid lateral buckling of the energy dissipater. The well confinement to the dissipater is realized by the enhanced restraining area that has sufficient vertical and horizontal stiffeners, as shown in Fig. 1(c). The thickness of the confinement plate is reduced by 2 mm to provide a gap to accommodate the higher mode out-of-plane buckling deformation of the dissipater panel, so that a larger deformability in the plane can be achieved. The confinement surface is attached by a layer of stainless steel shim to reduce the friction force once the dissipater is in contact with the confinement surface. The pair of buckling restrainers are connected through high-strength bolts but separated by the two partition plates, as shown in Fig. 1(a). Note that the buckling restrainers also serve as the connector to the main structural components using a similar mechanism of the L-shaped connectors. This mechanism prevents the buckling restrainer from sliding during the lateral loading and deformation.

3. Shape optimization design method based on J2 theory

A steel shear panel damper is often installed at positions with large deformations during a severe earthquake, such as two adjacent stories and the coupling beams. The damper commonly deforms in the plane and the entire area is supposed to yield simultaneously under the pure shear force. However, the moment associated with the shear force often results in an early yielding at the four corners where the largest equivalent stress exists. The J2 theory to define the yield criterion can thus be used to develop the yield line of the panel under the shear force. A more complex load condition of the damper bearing both axial and shear forces can also be considered within the J2 theory framework.

3.1. Derivation of stress contour line under shear force

3.1.1. Type 1: Optimized by von Mises yield criterion (J2 theory)

The thickness of the panel is uniform and defined as t. The given height is denoted as h. The panel is symmetrical on the vertical and horizontal axes. The xoy coordinate system is defined with the origin at the center of the panel, as shown in Fig. 2. The height is along the x axis. The left side of the damper is assumed to be fixed as the constraint boundary, while the right side moves vertically as the loading direction. The rotation about the z axis (out of plane) at the right side is prohibited, while the deformation along the x direction is free. Considering the yielding mechanism, a small deformation is assumed. At any section perpendicular to the x axis, the shear stress is assumed to be uniformly distributed along the cross-section, while the normal stress has a linear distribution with the maximum at the both ends and zero at the middle point.

Given the designed yield force as V, the stress state of a micro unit in the plane at any point (x, y) is as shown in Fig. 2, where σ and τ represent the normal and shear stress respectively, and θ_p is the direction angle of the principal plane where the shear stress is zero. According to the equilibrium of the micro unit, the direction angle can be calculated as Eq. (1), and the two principal stresses in the plane are expressed as Eqs. (2) and (3), respectively:

$$\tan 2\theta_p = -\frac{2\tau_{xy}}{\sigma_x - \sigma_y} \tag{1}$$

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2} \tag{2}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2} \tag{3}$$

By applying the J2 yield criterion [24] and introducing the stress condition that $\sigma_y = 0$, the equivalent von Mises stress, σ_e, is expressed as Eq. (4):

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + \sigma_1^2 + \sigma_2^2} = \sqrt{\sigma_x^2 + 3\tau_{xy}^2} \tag{4}$$

When the damper sustains the shear force V, the bending moment of a section M at x can be given as $M = Vx$. Suppose the shape function of the panel is $f_1(x)$, the maximum normal stress on the section at x is calculated by Eq. (5):

$$\sigma_x = \frac{M|f_1(x)|}{I_z} = \frac{3Vx}{2tf_1^2(x)} \tag{5}$$

where the moment of inertia about the z axis is $I_z = \frac{2}{3}tf^3(x)$.

The shear stress τ_{xy} introduced by the shear force V is actually distributed parabolically along the cross-section, but simplified as a uniform distribution:

$$\tau_{xy} = \frac{V}{2t|f_1(x)|} \tag{6}$$

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