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Cyclic behaviour of low-yield-point steel shear panel dampers

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ABSTRACT

In this paper, a new type of low-yield-point steel BLY160 is applied in the metallic shear panel damper device. To intensively investigate the seismic behaviour of the dampers, reversed cyclic loading tests are conducted to four groups of specimens, with the loading conditions and dimension parameters as test variables. The influences of the width-thickness ratio and corner perforation of the panel, the stiffening rib size and the cyclic load history are analysed. Through the experimental performance of test subassemblies, such as the hysteretic load-displacement loops, skeleton curves, deformation behaviour and failure modes, the earthquake mitigation effects of the damper devices are evaluated. In particular, conspicuous work-hardening is observed in the condition of cyclic deformation under both constant amplitude and increasing amplitudes loading. Contributed by the cyclic hardening of the low-yield-point steel, the energy dissipation capacities of the tested damper devices are approximately 1.5–2.5 times higher than that of a steel panel made of equivalent elasticity and perfectly plastic material. The complicated hysteretic performance with significant strain hardening can be accurately simulated by the kinematic-isotropic combined hardening model proposed in this paper, which incorporates the loading history effect by using the memory surface concept. The validity of the numerical model is verified by the comparison of the predicted cyclic behaviour and test responses.

1. Introduction

The passive energy dissipation method has been widely used in seismic controlled structures since the 1980s [1,2]. In a passive energy dissipation system, energy dissipation devices are installed to the structure system to enhance structural damping, stiffness and strength. These devices ultimately aim to absorb the input energy of wind and earthquake excitation; hence, damage to the parent structures can be minimized. Passive energy dissipation devices can be generally classified by the following operational mechanics: yield of the metals, friction sliding, phase transformation of the metals, fluid orificing, electromagnetism induction resistance and deformation of viscoelastic solids or fluids. In particular, the metallic dampers possess the advantages of simple fabrication, definite stressing state and stable mechanical performance. As a result, utilizing the elasto-plastic deformation of the metallic materials has become one of the most popular methods for energy dissipation.

Over the last several decades of research, many types of metallic energy dissipation devices have been proposed, including the torsion beam, bending beam, parallel stiffened plates, buckling restrained brace and shear panel dampers [3–5]. These metallic dampers differ in the operation principle of bearing mechanics, leading to the different cyclic behaviour under reversed loading. The parallel plates which make use of the flexural deformation of metals usually rely on the multiple plates to build up the required stiffness and damping. These patented ADAS [6] originates from the simple shape of the hourglass [7], and several variants have been derived as the triangularly shaped TADAS [8], the honeycomb damper [9] and the slit steel damper (SSD) [10]. The shape of the plate is designed according to the distribution of the bending moment along the height, and it aims to facilitate the material of the damper yield simultaneously. The buckling-restrained brace (BRB) [11], however, absorbs the input energy through the axial deformation of the metal. The braces are often diagonally installed in the frame structures, which transform the lateral drift of buildings into the axial press or pull deformation of the dampers. In particular, among the popular energy dissipation devices, the shear panel dampers are designed to resist the in-plane shear. The elasto-plastic deformation is supposed to spread over the entire panel plate in the condition of pure shear loading, and thus, the panel dampers behave the properties of large initial stiffness, high ultimate bearing capacity and favourable energy dissipation ability. In recent researches, several novel typologies of metallic shear panel devices have been proposed to improve the hysteretic

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performance, such as (i) the buckling inhibited shear panels with sandwich configuration, which apply the external steel or concrete layers to the base plates for providing the effective lateral restraints [12–14]; (ii) the perforated shear panels, which are designed to achieve the required in-plane stiffness though introducing the holes with different shapes, sizes and arrangement patterns [15–18]; and (iii) the ring-shape plates shear walls in a unique pattern of cutouts, which consists of the ring-shaped steel portions connected by diagonal links and absorbs the energy by the mechanics of plastic deformation from a circle shape into an ellipse [19]. In addition, some studies focus on the simulation, optimization and design strategies for the shear panel devices as well as the structure systems, which aim at a stable energy dissipation capability and seismic resistance response with economical material usage [20–24].

Aside from the structural innovation of the energy dissipative devices, numerous alternative metallic materials have been applied in the manufacture and design of metallic dampers, such as aluminium, lead, mild steel, copper and shape memory alloys [25–28]. In particular, as reported in previous researches, low-yield-point steel has characteristics of relative lower yield point and high plastic deformation ability, which enable the steel damper to enter the yield phase early and to remain working under large deformations [29–34]. In addition, mild steel presents the conspicuous strain hardening and leads to the expansion of the cyclic loops area, which can be also observe in the experiment of other low strength-high hardening materials such as pure aluminium [31]. Thus, using low-yield-point steel instead of conventional structural steel can enhance the energy dissipation capacity of the hysteretic dampers.

As concluded by De la Llera et al. [27], in generally, a good metallic device for seismic applications must exhibit the following characteristics: (1) adequate elastic stiffness to withstand in-service lateral loads such as wind or earthquakes; (2) a yield strength of the damper exceeding the expected in-service loads; (3) large energy dissipative capability; and (4) a stable hysteretic force-displacement response that can be modelled numerically. Based on the previous analysis, the shearing-type damper made of low-yield-point steel utilizes the high in-plane stiffness and the dissipative capability of shearing actions in panels, which take advantages of the structural form and advanced material so that it perfectly meets the former three mechanic requirements for energy dissipation devices [32–34]. As for the aspect of numerical calculation, constitutive models are proposed to simulate the hysteretic behaviour of the dampers. While the simpler bilinear model is usually used by researchers for the sake of convenient calculation, some other sophisticated models have been adopted to capture the complex features observed in experiments. To describe the smooth transition portion from elastic to inelastic phase, the nonlinearity is introduced by the Bouc–Wen model [35] and the Ramberg–Osgood [36] model, which replace the straight-line segments with a curved line. However, these models are generally initiated with the kinematic hardening rule, which is out of the ability to simulate the significant work-hardening effect with the accumulated plastic strain under cyclic loading. The concept of the combined hardening model is then proposed by dividing the increase of the stress into two portions that individually comply with the kinematic hardening and isotropic hardening rules [37].

In spite of the extensive studies of both low-yield-point steel and the corresponding shear panel dampers in the literature, the data on test performance and numerical analysis focus almost exclusively on the LYP100 and LYP235 steel manufactured by the Nippon steel corporation in Japan [38,39]. With the increasing requirement for low-yield-point steel, the Chinese Baosteel Corporation developed a new type of mild steel named BLY160, which has been applied in the buckling restrained brace (BRB) and behaves good energy consumption ability [40]. However, the application performance of LYB160 in the shear panel dampers lacks test investigation, especially under the condition of cyclic loading. Accordingly, sophisticated numerical models are also required to simulate the hysteretic behaviour of the dampers, with tracing the evolution of the cyclic hardening and incorporating the influence of the loading history.

In this paper, test investigation and numerical analysis are conducted for the cyclic behaviour of the low-yield-point steel shear panel damper (LSSPD). To make full use of the material, the shear panel plates are made of low-yield-point steel, which is strongly constrained by the flanges and stiffeners made of ordinary structural steel. Reversed cyclic loading tests were first conducted to a total of 10 full-scale specimens, and the subassemblies were divided into four groups with the loading conditions and dimension parameters as test variables. The hysteretic load-displacement loops, skeleton curves, shearing deformation of the steel panels and fatigue failure modes are discussed in details, and the influences of panel width-thickness ratio, stiffening rib size and cyclic load history are focused upon. In addition, the evaluation of the energy dissipation capacity and the feature of significant strain hardening are intensively analysed. Finally, a numerical calculation method is presented to simulate the hysteretic behaviour, and the model parameters are calibrated by the test data. The accuracy of the proposed model is verified though the comparison of the simulated and measured response under cyclic loading.

2. Test program

2.1. Material properties

In designing the metallic hysteric damper, the steel employed in damper devices is supposed to become plastic prior to the other structural components such as columns and beams. This aim can be easily achieved by decreasing the yield strength of the steel. With the increasing popularity and demand for low-yield-point steel, a new type of low-yield-point steel, BLY160, has been developed by the Chinese Baosteel Corporation [41–43]. This steel is designed to have a yield point of 160 MPa and the following methods are used to decrease the yield strength and increased elongation: (i) adopting similar chemical components to pure iron by reducing the alloy content; (ii) increasing the ferrite grain size; and (iii) tying up the carbon and nitrogen atoms by adding alloying elements such as titanium or niobium. The chemical composition of BLY160 steel, as summarized from the mill certificate, is shown in Table 1.

To clarify the mechanical properties of the steel coupon, a uniaxial tensile test was first conducted to obtain the basic material parameters listed in Table 2, including the elasticity modulus (E), yield stress (f_y, measured via 0.2% method), ultimate stress (f_u), and elongation at break (EL).

The behaviour of BLY steel under monotonic loading is compared with other general structural steel (SS400 and SS490) and another low-yield-point steel manufactured by Nippon (LYP235) as shown in Fig. 1. The characteristics of BLY160 steel and its advantages in engineering applications can be summarized as follows: (i) the yield stress of BLY steel is much lower than that of structural steel, which enables dampers made of BLY steel to enter the plastic phase early for energy dissipation under small deformations; (ii) the ultimate stress is greater than 2 times that of the yield stress, and the hardening of the stress with the accumulation of plastic strain contributes to the energy dissipating capacity for the seismic action; and (iii) the stress hardening without deterioration occurs until the strain reaches 30%, and the elongation at break is approximately 56%. The favourable ductility ensures the deformability against intensive earthquakes.