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Cyclic tests for unbonded steel plate brace encased in reinforced concrete panel or light-weight assembled steel panel

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ABSTRACT

Cyclic loading tests for the panel buckling-restrained brace (panel BRB) comprising an unbonded steel plate brace encased in a panel were carried out to investigate constructional details of a novel type light-weight assembled steel panel and to study reinforcement forms to improve the punching shear capacity of reinforced concrete panel. The effects of unbonded materials and gaps between the panel and the brace, reinforcements in concrete panels and weight of panels on the hysteretic behavior of panel BRBs, were mainly examined. Tests reveal that, compared with additional steel bars and ties, perforated steel channels used as reinforcements along the entire length of brace can prevent concrete panels from failure by punching shear. Residual flexural deformations appeared in some braces due to the gaps. The maximum axial compressive strength of each specimen significantly exceeds its yield strength due to strain hardening and frictional action. Lubricating greases in the steel panel BRBs are helpful to reduce the frictional action and to achieve satisfied hysteretic responses. All specimens achieved great ductility and energy dissipation capacity. The concrete panel in one specimen failed by punching shear and the other specimens failed due to tensile fracture of the braces. The weight of the assembled steel panel is about 30% that of the concrete panel and the hysteretic behavior of the steel panel BRBs matches that of the concrete panel BRBs. The panels that can be assembled and disassembled would be advantageous in inspecting and replacing the braces, as well as in reusing the panels.

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1. Introduction

The buckling-restrained brace is usually composed of an inner core steel brace to carry axial loads and outer restraint parts to prevent the core brace in compression from large amplitude buckling [1,2], facilitating efficiently using the compressive bearing capacity and energy dissipation capacity of steel brace members, and it has become popular in modern structures. For the working behavior of a buckling-restrained brace anticipated in design, axial loads are only resisted by the core brace, yielding of the buckling-restrained brace is limited in the core brace and the outer restraint parts, which provide continuous lateral bracing for the core brace and don't resist any axial loads, remain elastic. To realize the expected behavior above, an unbonded material layer or a gap is commonly employed between the core brace and the restraint part to eliminate force transfer and to allow the lateral expansion of the core brace in compression [1,2]. Depending on the configuration of outer restraint part, there exist two categories of buckling-restrained braces. One is panel type BRB (panel BRB) employing a reinforced concrete panel as the restraint part [1,2], and the other is bar type BRB (BRB) using steel members or a steel tube filled with concrete, etc. as the restraint part. The BRB has been used widely and was studied by lots of researchers, such as Blacks et al. [3], Tramblay et al. [4], Iwata and Murai [5] and Chou and Chen [6]. Especially, to facilitate the quality control, two restraint parts were used to sandwich the core brace in the researches [4–6]. Meanwhile, investigations on seismic performance of buckling-restrained braced frames (BRBFs) have been widely conducted by Sabelli et al. [7], Fahnestoch et al. [8], and Tsai et al. [9], and design criteria for the BRBFs have been provided in the 2010 AISC Seismic Provisions for Structural Steel Buildings [10]. In applications, the panels can be used for partition in buildings except for acting as restraint members for the core braces. Therefore, compared with the BRB, the panel BRB is a better substitute when more partition walls are required in the buildings, such as hospitals, hotels, administration houses, and so on. Many studies were focus on constructional details to improve hysteretic behavior of the panel BRBs in which the panels were made of reinforced concrete. The first tentative test conducted by Yoshino et al. [11] indicates that gaps between the brace and the panel had great influences on ductility of the panel BRBs. The effects of reinforcement details, as well as unbonded materials, on the hysteretic behavior of the small scale panel BRBs were experimentally investigated by Wakabayashi et al. [12]. Inoue et al. [13] conducted a theoretical analysis and cyclic loading tests to study the overall buckling behavior of the panel BRBs and to examine a kind of reinforcement at the ends of panel. Ding et al. [14] examined the effects of constructional details on the hysteretic behavior of diagonal and chevron panel BRBs by tests and found that

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the punching shear capacity of the panels is directly affected by the details of unbonded materials. For the panels made of reinforced concrete, except that main bars were placed on both sides of the brace in two perpendicular directions, additional steel bars were used as reinforcements around the core braces to improve the punching shear capacity of panels [12,14].

Based on the tests mentioned above, it was found that punching shear failure of reinforced concrete panels still occurred although the reinforcements formed by additional steel bars around braces were helpful to improve the punching shear capacity of panels [12,14]. Moreover, dense steel bars around braces would make it difficult to ensure the quality of concrete pouring. These unfavorable aspects indicate that further investigations for new forms of reinforcements are needed. In addition, for the tests conducted by Wakabayashi et al. [12] and Ding et al. [14], flat stiffeners (the thickness direction of stiffeners is the same as that of core plate brace) were welded to the ends of plate brace to avoid impairing steel bars and reinforcements near the ends of panel. When soft materials were glued on the ends of the stiffeners to allow the core brace in compression to deform freely without crushing the concrete panel, gaps formed between the panel and the brace near the ends of stiffeners were slightly larger, resulting in punching shear failure of panel near the ends of the stiffeners [12,14]. Therefore, for the purpose of exploring new reinforcements of panel along the length of brace, a kind of perforated steel channel was proposed to improve the punching shear capacity of panel, to ensure the pouring quality and to facilitate the distribution of main bars. Meanwhile, upright stiffeners (the thickness direction of stiffeners parallels the width direction of core plate brace) were used to reduce the size of gaps near the ends of stiffeners and the effects of the flat and the upright stiffeners on working behavior of panel BRBs were examined.

Up to now, for the panel BRBs in researches and applications, the reinforced concrete panels are integrally formed [11–14]. It is difficult to inspect and repair the core brace after severe earthquakes and the panel formed integrally cannot be reused if the core brace needs to be replaced. Special formworks need to be manufactured for concrete pouring and the quality control is usually difficult. Furthermore, the weight of concrete panel is large, which is disadvantageous to seismic performance of panel BRBs and panel installation. Especially, cracks or failure of the panel would occur due to bending moments and punching shear forces applied by the core brace in compression [12,14–16]. It is well known that the punching shear failure is brittle and it deteriorates ductility and energy dissipation capacity of panel BRBs. These factors described above have prevented the panel BRBs from good applications. To solve these problems, a novel type assembled steel panel is proposed to decrease the weight of panel, to facilitate inspecting and replacing the core brace, to ensure the quality of fabrication and to reuse the panel. Thus, constructional details, interaction between the assembled panel and the brace, hysteretic behavior and failure mechanism for the assembled steel panel BRBs need to be addressed.

In this study, cyclic loading tests for three concrete panel BRBs (PBRBs) and two light-weight assembled steel panel BRBs (SPBRBs) were conducted. The effects of stiffeners in steel braces, unbonded materials and gaps between the panel and the brace, configurations of reinforcements in concrete panels, the weight of panels, etc. on the hysteretic behavior of the panel BRBs have been investigated.

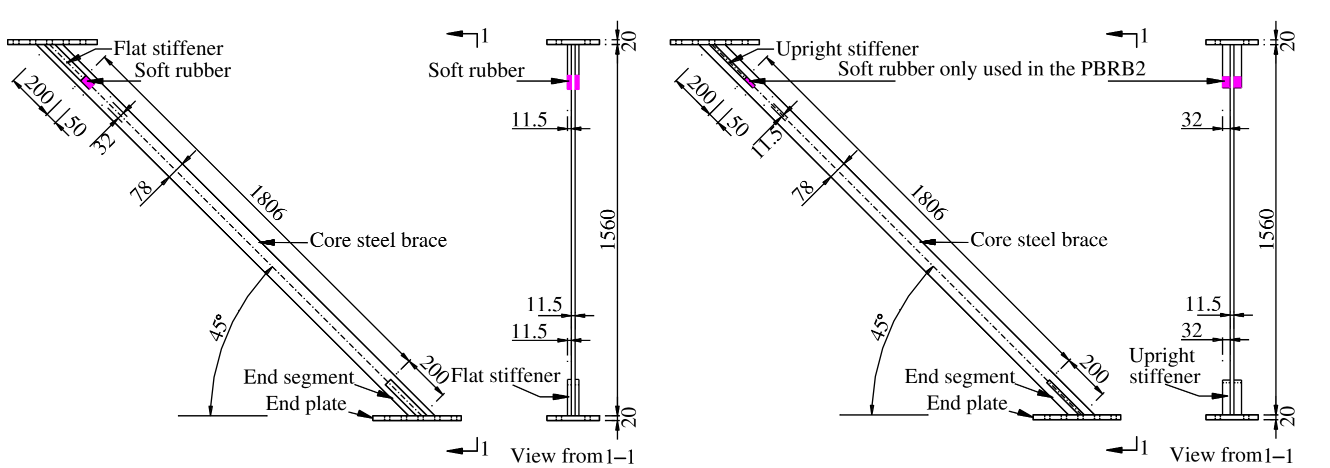
2. Test arrangements

2.1. Test specimens

2.1.1. Outline of specimens

Three specimens with the concrete panel are labeled PBRB1, PBRB2 and PBRB3 and two specimens with the assembled steel panel are labeled SPBRB1 and SPBRB2, shown in Figs. 1–5. All dimensions are in millimeters. The constructional details of the specimens PBRB1, PBRB2 and PBRB3 are shown in Figs. 1–4 and 6. In order to isolate the adhesion between a steel plate brace and a concrete panel, each plate brace in the specimens PBRB1, PBRB2 and PBRB3 was wrapped with unbonded materials and then encased in the reinforced concrete panel (Fig. 4(a) and (b)) in which main bars were placed on both sides of the brace in two perpendicular directions with regular spacing of 95 mm. Main ties were used to connect the main bars through the thickness of panel with regular spacing of 285 mm (Figs. 2 and 3). Moreover, edge reinforcements were embedded in panel to prevent the edges of concrete panel from failure by punching shear. The edge reinforcements in the PBRB1 were formed by welding anchor bars to embedded plates and those in the specimens PBRB2 and PBRB3 were formed by welding perforated channels to embedded plates (Figs. 2 and 3). Besides, two forms of reinforcements were employed in concrete panel along the entire length of a brace. One is additional steel bars connected by additional ties in the PBRB1 (Figs. 2, 4(a) and 6(a)), and the other is two perforated channels connected by short channels in the specimens PBRB2 and PBRB3 (Figs. 3, 4(b), 6(b) and (c)).

The constructional details for the specimens SPBRB1 and SPBRB2 are shown in Figs. 1(b), 4(c), Figs. 5 and 7. The numbers in parentheses in Fig. 5 show the dimensions for the SPBRB1. Each assembled panel was composed of two identical frameworks and profiled sheets. The two frameworks were connected together by self-drilling screws, splice plates and high strength bolts, causing the two parts to act as a unit



a) Plate braces in the specimens PBRB1 and PBRB3. b) Plate braces in the specimens PBRB2, SPBRB1 and SPBRB2.

Fig. 1. Details of the plate braces for the panel BRB specimens. (a) Plate braces in the specimens PBRB1 and PBRB3. (b) Plate braces in the specimens PBRB2, SPBRB1 and SPBRB2.

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