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Cyclic tests of unbonded steel plate brace encased in steel–concrete composite panel

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A R T I C L E I N F O

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A B S T R A C T

Cyclic loading tests for the panel buckling-restrained brace (panel BRB) comprising an unbonded steel plate brace encased in a novel type profiled steel sheet–concrete composite panel were carried out to mainly investigate the effects of construction details of profiled steel sheets and perforated steel channels on the hysteretic behavior of the panel BRBs. Two loading stages, including increasing and constant amplitudes of horizontal displacement in the first and the second stages respectively, were used for six panel BRB specimens. Tests reveal that the perforated channels can prevent the composite panels from failure by punching shear. When stiffening ribs of profiled sheets were installed parallel to the axis of the brace, the composite panels remained intact in general after two loading stages. When the stiffening ribs of profiled sheets were installed in the horizontal or vertical direction, the specimens in which welds were used for the grooves of profiled sheets near the brace can also prevent panels from failure in the two loading stages, and bending failure of panels occurred in the first loading stage for the specimens without welds for the grooves of profiled sheets. The specimens, in which failure of panels was avoided, achieved great ductility and energy dissipation capacity before tensile fracture of steel braces occurred. Due to strain hardening and frictional action, the ultimate axial compressive strength of each specimen significantly exceeds its yield strength.

1. Introduction

The panel buckling-restrained brace (panel BRB) is a typical form of buckling-restrained brace (BRB) and it usually consists of one or two unbonded steel plate braces and an encasing panel [1–4] (Fig. 1). For the working behavior of a panel BRB anticipated in design, axial loads applied to the panel BRB are only resisted by the core brace, yielding of the panel BRB is limited in the core brace, and the panel, which provides continuous lateral bracing for the core brace and doesn't resist any axial loads, remains elastic in general. As shown in Fig. 1, to realize the expected behavior above, unbonded materials or gaps are usually employed between the core brace and the panel to eliminate force transfer and to allow the lateral expansion of the core brace in compression [1–4]. In applications, the panel BRBs can be well used in the steel structures in which more partition walls are required, such as high-rise hotels, apartment buildings, schools, and so on [3,4]. Up to now, for the panel BRBs in applications and researches, the panels are made of reinforced concrete [1–14].

Lots of studies, including test researches carried out by Yoshino et al. [5], Wakabayashi et al. [6], Inoue et al. [7], Li [8] and Ding et al. [9] and theoretical studies done by Inoue et al. [10], Odajima et al. [11] and Ding [12], focused on the construction details to improve the working behavior, especially the punching shear capacity of the panel, for the reinforced concrete panel BRBs. The details examined in these researches include gaps and unbonded materials between the panel and the core brace, reinforcements in the panel, and so on. Based on the test researches above, it was found that, due to punching shear forces applied by the encased brace, severe cracks and failure by punching shear still occurred in the concrete panel although the reinforcements usually formed by the additional steel bars around the braces are helpful to improve the punching shear capacity of panel [6,8,9,13], indicating that further studies for construction details to avoid severe cracks and failure by punching shear for the panel are needed.

According to applications and the researches above, some disadvantageous aspects for the reinforced concrete panels in the panel BRBs are as follows: (1) additional formworks are needed for pouring concrete, and quality control for initial crookedness of encased brace is difficult; (2) especially, tension strength of concrete is very low as compared with that of steel, and therefore cracks and failure of concrete panel often occurred under punching shear forces applied by the encased brace [6,8,9,12,14]. It is well known that the punching shear failure is usually brittle and it greatly deteriorates the ductility and energy dissipation capacity of panel BRBs; and (3) dense steel bars are usually added near the core brace to improve the punching shear capacity of the panel. Consequently, the dense steel bars will likely result in

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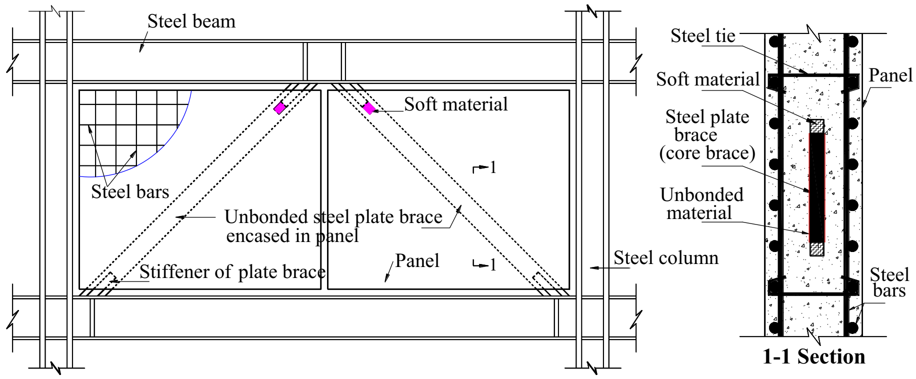

Fig. 1. Panel buckling-restrained braces installed in steel frames.

difficulty in pouring concrete and quality control. The drawbacks above have prevented panel BRBs from wide application. Therefore, it is necessary to explore new kinds of panel BRBs to substitute for the reinforced concrete panel BRBs.

In a panel BRB, the panel is mainly used to resist out-of-plane transverse loads applied by the core brace and it is usually designed as a flexural member. The working behavior of the panel is similar to a beam or a floor slab to support transverse loading. In applications, profiled steel sheet–concrete composite slabs have become popular in recent years, in which the profiled sheets are usually used as formworks to facilitate pouring concrete and also used as components to resist tension forces [15,16]. Being inspired by the configuration of the composite floor slab and taking into account the disadvantageous aspects of reinforced concrete panel BRBs above, a novel type of unbonded steel plate brace encased in the profiled steel sheet–concrete composite panel was proposed and described as follows: (1) to improve the flexural capacity of the panel and to act as formworks for pouring concrete, two layer steel sheets were used as outer skins and the concrete was placed between the two skins. The reason for employing two layer sheets as surfaces of the panel is that, due to the initial crookedness of the encased brace, punching shear forces applied by the brace in compression, etc., two surfaces of panel will be in tension simultaneously; (2) to develop good composite action between steel sheets and concrete core and to resist separation and slippage between steel sheets and concrete, a special form of profiled steel sheet, called as ‘flat profile’ in the design code [16], was used; and (3) to improve the punching shear capacity of panel and to facilitate concrete pouring also, a proposed steel channel with the perforated web was employed in the panel along the length of brace. For the unbonded plate brace encased in this type of composite panel, some questions, including the effect of construction details on hysteretic behavior of panel BRBs, composite action between the concrete core and two layer steel sheets, interaction between the composite panel and the brace and failure mechanism of composite panel BRBs, need to be addressed.

In this study quasi-static tests for six specimens of diagonal unbonded steel plate brace encased in the profiled steel sheet–concrete composite panel (CPBRBs) were conducted, and the effects of construction details of the profiled steel sheets and the perforated channels on both hysteretic behavior and failure mode for the CPBRBs have been mainly examined.

2. Test arrangements

2.1. Test specimens

2.1.1. Outline of specimens

The six specimens are labeled CPBRB1 to CPBRB6 and each specimen comprises a diagonal unbonded steel plate brace encased in a composite panel, shown in Figs. 2–7. All dimensions are in millimeters. The composite panel is composed of two outer layer profiled steel sheets filled with concrete. Fig. 2(b) shows the configuration and the cross section for the profiled steel sheet, which is referred to as ‘flat profile’ in the design code [16], and it should be noted that there exist grooves along the cold formed stiffening ribs in the profiled sheets. In order to isolate the adhesion between an encased steel plate brace and an encasing composite panel, the plate brace was wrapped with unbonded materials and then encased in the composite panel. Perforated channels embedded in concrete along the entire length of brace were used as reinforcements for

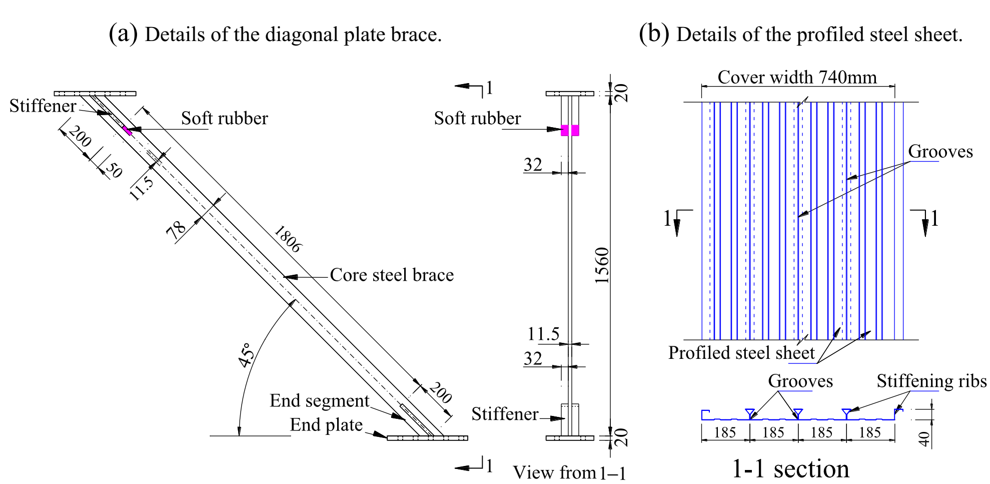

Fig. 2. Details of the plate brace and the profiled steel sheet for the CPBRB specimens (unit: mm). (a) Details of the diagonal plate brace. (b) Details of the profiled steel sheet.