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Cyclic tests for steel frame with unbonded steel plate brace encased in panel

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ABSTRACT

Quasi-static tests for two panel buckling-restrained braced frames (panel BRBFs), each of which consists of one two-story steel frame and two diagonal or chevron-shaped panel buckling-restrained braces (panel BRBs), were done to examine the impacts of constructional details on hysteretic response of the panel BRBFs (PBRBFs). Each panel BRB consists of one unbonded steel brace and either one assembled steel panel or one steel-concrete composite panel. Obvious yielding of panel BRBs and framing members developed from inter-story drifts of approximately 1/375 and 1/75 respectively. Local buckling of unreinforced segments of beams occurred when story drifts nearly reached 1/50. Local buckling of columns and tension fracture of steel components occurred at story drifts far larger than 1/50. The PBRBFs didn't fail within story drifts of 1/30 in the first load stages and still exhibited stable behavior before eventual failure, which was attributed to tension fracture of either encased braces or other components, in the second load stages. The skeleton curves of each specimen are close to a trilinear model and those of both panel BRBs and frame are close to a bilinear model. All panel BRBs exhibited good ductility and qualified cumulative inelastic deformation capacity. The tests revealed that the capacity design generally confines most inelastic action in panel BRBs within story drifts of 1/50. The constructional details, including configurations of panel BRBs, width-to-thickness ratios of elements that meet moderately ductile requirement for H-shaped framing members, strengthening measures and connections, were generally acceptable to ensure good performance of the panel BRBFs.

1. Introduction

The panel buckling-restrained brace (panel BRB) can be used in the concentrically braced steel frames [1–3]. Usually, a panel BRB, being a kind of buckling-restrained braces (BRBs) [1–4], uses one wall panel to provide one or two unbonded core steel braces with lateral restraint [1–3,5–9]. For example, the panel BRBs installed in steel frames are shown in Figs. 1, 2(a) and 3(a). For a panel BRB subjected to large cyclic loads, besides yielding in axial tension, the core brace in axial compression can also yield if lateral restraint of the encasing panel (restraining remember) for the core brace is adequate [5,6,9]. Here the lateral restraint is the capacity of restraining remembers and usually includes two aspects. One is flexural stiffness to avoid global buckling and is usually evaluated by a parameter called restraining ratio [10], defined as the ratio between the overall elastic buckling load of the restraining remember and the axial yield strength of the core for a BRB [1,2,10–15]; the other is the capacity to avoid local failure and is usually designed to resist local punching shear forces of the core brace developing high-mode buckling within the restraining member [6,9,15–19]. Depending on the type of BRBs and the demand of axial deformations of BRBs, requirements for the capacity to avoid overall buckling or local failure are different [10–19]. Since unbonded layers or air gaps are reserved between the brace and the panel, the axial strength of a panel BRB is intended to be totally provided by the core plate brace. Panel BRBs can be used not only as steel braces but also as partition walls in buildings, such as schools, hotels, apartment houses, etc. [1,20]. Recently, two novel type panel BRBs were proposed and tested by Ding [21,22]. One is a steel brace sandwiched in a light-weight assembled steel panel [21], the other is an unbonded brace embedded in a composite panel [22]. Hysteretic behavior of the panel BRBs is stable and excellent prior to failure, and their failure is mainly attributed to tension fracture of encased braces as the panels remained intact

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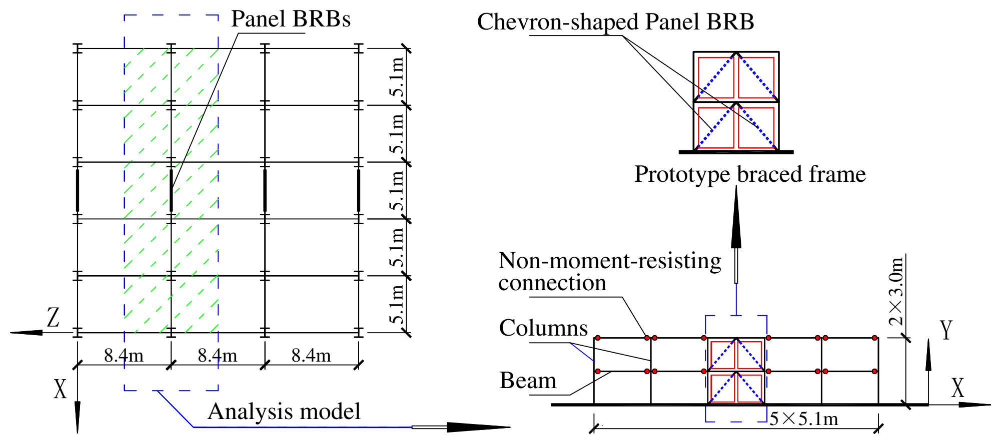
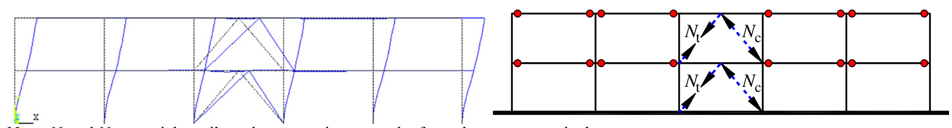


(a) Plan and elevation views for prototype building.



Note: N_t and N_c are axial tensile and compressive strength of core braces, respectively.

(b) The first-mode response of the analysis model

Fig. 1. Prototype building models.

[21,22]. Compared with the panel BRBs with the reinforced concrete panel [5–9], punching shear failure of panel was avoided for the proposed panel BRBs [21,22] and ductility of them was actually improved, revealing that the two type panel BRBs are available to the application of panel BRBFs in future.

Constructional details for steel frames with the buckling-restrained braces (BRBs), referred to BRBFs, directly affect the seismic behavior of the BRBFs [23–28]. Usually, a BRB member connects to framing members by gusset plates [23–29], which connect to the flanges of framing members at the moment resisting beam-to-column connections [23,24,27,28]. Although many BRBs in the component tests exhibited super seismic behavior with high ductility, substantial energy dissipation and excellent cumulative plastic axial deformation capacity, some researches revealed that unwanted failure modes in the BRBFs, such as out-of-plane buckling of the gusset plates along with the BRBs [23,29], fracture of welds between the gusset plates and the framing members [23,27,28], etc., deteriorate the good performance of the BRBs that they exhibit in the BRB component tests. Besides, gusset plates welded at the beam-to-column connections increase stiffness of both the connections and the moment resisting frames to resist lateral loads while transferring bending moments to the BRBs, which would further affect working behavior of the BRBs that are intended to be used as axially loaded members.

For steel frames with the panel BRBs (panel BRBFs), characters of both framing members and panel BRBs, connection types and details, interactions between the steel frames and the panel BRBs, etc. would directly affect their working behavior also. Up to now, only two tentative tests were conducted on steel frames with the reinforced concrete panel BRBs [7,8]. The tests revealed that cracks or punching shear failure of the concrete panel would occur [7,8]. The brittle failure of panel deteriorates the ductility and energy dissipation capacity of panel BRBs [6–8,21]. As the proposed panel BRBs with either the assembled steel panel or the steel-concrete composite panel exhibited good ductility in the previously component tests [21,22], it needs to ensure that they can also have good performance when they are used as steel braces in the concentrically braced steel frame. Therefore, it is worthwhile to explore configurations to improve hysteretic behavior, to avoid the disadvantages mentioned above and to get some guides for application of the panel BRBFs.

In view of the needs above, tests were conducted for two two-story specimens, which are the PBRBF1 with diagonal panel BRBs and the PBRBF2 with chevron-shaped panel BRBs, to investigate the effects of the constructional details on the hysteretic behavior of the PBRBFs. The objective of the tests, along with the constructional details, for two panel BRBFs (PBRBFs) are outlined as follows: (1) two specimens were tested to mainly examine effects of configurations of panel BRBs (diagonal and chevron-shaped) and the brace-to-framing member connections on the performance of the specimens. (2) based on the inclination angles of encased braces in each specimen, each end of the encased brace was directly welded to the flange plate of either a beam or a column to replace large gusset plate connections and to mitigate the impact of the in-plane bending moments on the brace; (3) to ensure stable behavior of panel BRBs, segments of framing members attached to encased braces were strengthened to prevent out-of-plane failure of the panel BRBs, which would be induced by inelastic deformations of the segments of framing members; (4) to examine the impacts of the type of the panel BRBs, both the assembled steel panel BRBs and the steel-concrete composite panel BRBs [21,22] were used in one PBRBF specimen; and (5) a capacity design was used to confine most inelastic action of the PBRBFs in the panel BRBs while preventing the framing members, especially the columns, from large inelastic deformations within the inter-story drift of 1/50, and therefore the framing members and connections were designed and strengthened based on the adjusted strength of the panel BRBs. Besides, the maximum inter-story drift level of 1/30 was employed to further examine the working behavior of the PBRBFs.

2. Arrangements for cyclic tests of PBRBFs

2.1. PBRBF specimens

2.1.1. Design of PBRBF specimens

Prototype braced frames were defined to provide a guide to get the scaled-down PBRBF specimens. Braced steel frames, with either