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Development and experimental validation of an assembled steel double-stage yield buckling restrained brace

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ABSTRACT

A novel assembled steel double-stage yield buckling restrained brace (DYB) was experimentally studied. The DYB core plate comprises one small core plate and one large core plate connected in series. The deformation capacity of the small core plate is restricted by a stopper mechanism. The deformation of the DYB is first concentrated at the small core plate and then shifted to the large core plate once the stopper mechanism is triggered, resulting in double-stage yield behavior of the DYB. Three specimens were fabricated with core plates of different size to study the main influencing factors in the design of DYBs. Quasi-static tests were conducted. Results from a comprehensive experimental study demonstrate that the DYB has a ductile, stable, and repeatable hysteretic behavior. It is a reliable and practical alternative to conventional framing systems in that it can enhance the earthquake resistance of existing and new structures and provide the rigidity needed to satisfy structural drift limits while delivering a stable and substantial energy absorption capacity. The proposed hysteretic model of the DYB was calibrated with the test results, showing good agreement and the capacity to capture characteristic points of hysteresis curves.

1. Introduction

Buckling-restrained braces (BRBs) have been used extensively for seismic application in Japan following the 1995 Kobe earthquake [1] and increasingly used in the United States since a few years after the 1994 Northridge earthquake [2]. BRBs have also been extensively applied in other seismic regions [3–6].

The typical BRB has a ductile steel core, which is designed to yield in both tension and compression. To avoid global buckling in compression, the steel core is first placed inside a steel casing before the casing is filled with mortar or concrete. A nonbonding material or a small air gap between the steel core plate and mortar or concrete is provided to minimize the transfer of the axial force from the steel core plate to the mortar and steel casing. Moreover, the gap allows the expansion of the steel core plate under compression. Conventional BRBs, which adopt steel tube filled with concrete or mortar as restrained components, are commonly heavy, resulting in difficulties in transportation, lifting, and installation. To avoid such a weight disadvantage, a number of all-steel BRBs with large maximum ductility capacity and cumulative ductility capacity have been developed [7–13]. Compared with the case for BRBs having mortar-filled tubes as restraining components, the mass of the restraining components of all-steel BRBs can be reduced by around 40%. Additionally, all-steel BRBs have hysteretic properties that are more stable owing to the high manufacturing accuracy and reliable mechanical properties of steel.

BRB frames are desirable for seismic design and rehabilitation in terms of their superior ductile performance. The use of BRBs [14,15] with enhanced, stable hysteretic behavior has been shown to greatly improve the performance of steel braced frames [16–18]. However, this system is prone to residual lateral deformations or damage concentration over the building height [19–21]. Once the deformation is concentrated in a certain story, it increases appreciably in the story and a weak story may develop. Although conventional BRBs provide additional load-carrying capacity and stiffness, they do not provide a means of deformation pattern control. The inelastic response in structural members and residual drift in soft stories are two critical issues that make a building difficult to repair after an earthquake. There is thus a need to develop a device that can control structures such that they deform uniformly and that can dissipate energy under different earthquake hazard levels [22].

This paper presents the development of a novel BRB called the double-stage yield buckling restrained brace (DYB), which is an assembled all-steel BRB with double-stage yield behavior. The DYB can sustain large axial deformations without structural damage, and provides stable energy dissipation capacities for the corresponding design drift under

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the effects of frequent and moderate earthquakes. After a description of the mechanics and definitions of the equations governing the response of the DYB system, a series of experimental validations that demonstrate the behavior of DYBs under quasi-static cyclic loading is presented.

2. DYB behavior

The present paper investigates a double-stage yield strategy that uses multi-sectional BRB cores. In the braced frame, the small core plate component of the BRB yields earlier than the large core plate and the energy dissipation due to early yielding allows the braced frame to minimize the response under the effects of low- to mid-level earthquakes.

The composition of the DYB is similar to that of the conventional BRB. The assembly of the DYB is simple and rapid and does not require additional welding. Moreover, the core plate of DYB could be repaired/replaced by dissemble the bolts and the steel casing could be reused fore several times. As shown in Fig. 1, the main feature of the DYB is the tandem configuration of two conventional BRBs of different size. The DYB mainly consists of three parts: two conventional BRBs with different yielding strengths and a stopper mechanism. Different yield strengths and displacements can be achieved by designing different widths and yield lengths of the core plates of the two conventional BRBs. The stopper mechanism is set parallel to the small BRB using the slotted holes for bolt connections. Using the stopper mechanism, when the brace is subjected to an external force, the maximum deformation of the small BRB is limited within an arbitrarily designed value. As the force increases, the stopper mechanism is activated and the DYB deformation mainly concentrates on the large BRB. The stopper mechanism provides the same deformation limits for the small BRB in tensile and compressive directions. The performance of the DYB is thus symmetric when the DYB is under tensile and compressive deformation.

A partially exploded view of the DYB assembly is shown in Fig. 1. As mentioned above, the DYB consists of the following key components.

2.1. Core plate segment

The steel segment has a rectangular section, which consists of small and large core plates. The small and large core plate segments are cut from the original core plate, and smooth transition between the two parts avoids the concentration of stress. The lengths and widths of the two parts are determined by the design strength and deformation capacity. Two ribs are welded on both sides of the extension of the core plate mainly for the bolted connection. The two ribs also help ensure that the inelastic response is confined to the plate with reduced sections

2.2. Buckling-restrained mechanism

The mechanism is a steel casing composed of two U-shaped steel channels and two cover plates. Both ends of a U-shaped channel are slotted to allow axial deformation of the core plate. A nonbonding material, such as rubber or polytetrafluoroethylene (PTFE) with a thickness of 2 mm [23], is arranged between the channels and core plate. The nonbonding material can effectively minimize the transfer of the shear force between the core plate segment and U-shaped steel channels. The core plate segment is expected to experience low-amplitude buckling in higher modes owing to the restraining mechanism. The gap is 2 mm to allow for the expansion of the yielding steel core in compression.

2.3. Stopper mechanism

The stopper mechanism is obtained by means of bolted connections with differently sized slotted holes at the two ends of the core plate. As shown in Fig. 1, short and long slotted holes are respectively designed at the ends of the small and large core plates. The bolt holes on the channel of the corresponding plate are standard circular holes. The core plate can deform freely until the bolts come into contact with the edges of the slotted holes. With such a mechanism, the deformation capacity of the small BRB is controlled at a certain value by the length of the short slotted holes. The initial positions of the bolts are set in the middle of the corresponding holes; the mechanism then works in both tension and compression. The transition part of the core plate is bolted with U-shaped channels using a sufficient number of bolts to prevent dislocation between the buckling-restrained mechanism and core plate. Such a mechanism ensures that stress is uniformly distributed in the core plate under both tensile and compressive loads.

3. Hysteresis of the DYB

Fig. 2 shows the hysteretic response of the proposed DYB: a skeleton curve (solid line) and hysteresis curve (dash line), apparently revealing

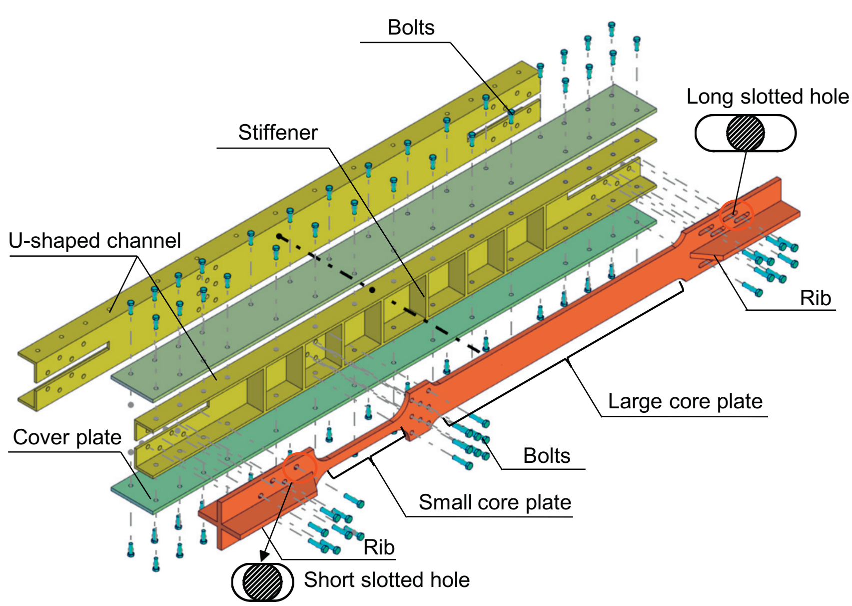

Fig. 1. Proposed configuration of the DYB.