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Seismic performance of fish-bone shaped buckling-restrained braces with controlled damage process

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ABSTRACT

A new type of all-steel fish-bone shaped buckling-restrained braces (FB-BRBs) with large maximum ductility and cumulative ductility have been proposed, and their excellent seismic performance and failure mechanism have been verified through a series of experiments in a previous study. The proposed FB-BRBs can fully utilize ductility of a material through a multiple-neck deformation mechanism. This mechanism can achieve a well-controlled damage process of different segments of the FB-BRBs. In addition, the proposed FB-BRBs can sustain tensile load-carrying capacity even after rupture of the core plate, which is owing to the interaction between the multiple stoppers of the core plate and corresponding filling plates. Both experimental and numerical studies have been conducted. However, the previous study failed to achieve the expected failure mechanism due to unexpected failure at the stoppers of the FB-BRBs. This paper aims to experimentally investigate the optimal values of the design parameters of the FB-BRBs, and further clarify the failure mechanism. Quasi-static cyclic loading tests were carried out using eight specimens with different configurations. Different failure modes of the newly proposed FB-BRBs are verified, and high seismic performance of the dampers is proved through the experimental results.

1. Introduction

Buckling-restrained braces can provide both stiffness and energy dissipation properties for structures, which have been widely employed in regions with a high seismic risk. With a metallic core plate enclosed by external restraining components, the core plate can have stable load-carrying capacity and high ductility under both tension and compression, while the load-carrying capacity of a conventional bracing decreases after occurrence of buckling, leading to poor ductility and low energy dissipation capacity. Under compression, both in-plane and out-of-plane buckling of the core plate occur, and the buckling mode changes gradually from the fundamental one to higher ones as the compressive deformation increases [1], where compressive and local bending deformation occurs in the core plate. Unbonding material is commonly employed to reduce contact forces between the core plate and the restraining components. Generally, BRBs are apt to fail due to core plate rupture at a necked region under tensile deformation. In addition to global [2,3] and local buckling [4], BRBs can also fail due to ultra-low cycle fatigue [5,6] at welds or base metal of the core plate.

Besides strength and stiffness, ductility is also a critical concern during structural design for BRBs. Two indices are generally adopted for ductility evaluation of BRBs. One is the maximum ductility index, μ_{max}, and the other one is the cumulative ductility index, μ_c, which can be respectively acquired as follows,

$$\mu_{max} = \frac{\Delta_{max}}{\Delta_y}, \mu_c = \frac{\sum \Delta_{p,i}}{\Delta_y} \tag{1}$$

where Δ_{max} is the maximum displacement of the yielding portion of the core plate; Δ_y is the corresponding yield displacement; $\sum \Delta_{p,i}$ is the accumulated plastic displacement. These variables are all obtained with regard to the yielding portion of the core plate. The maximum ductility index can also be defined as the ratio of the maximum displacement to the yielding length of the core plate, termed as the maximum average strain, ε_{max}, in this study. The cumulative ductility index can also be defined in terms of energy as follows,

$$\mu_c = \frac{\sum E_{p,i}}{E_y} \tag{2}$$

where $\sum E_{p,i}$ = accumulated plastic energy; E_y = stored energy till yielding of the core component.

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Besides the cumulative ductility index, μ_c, there is an alternative index, termed as cumulative inelastic deformation, ε_c, which can also be employed to evaluate the cumulative ductility capacity. ε_c is given by the following equation,

$$\varepsilon_c = \sum \varepsilon_p \tag{3}$$

where ε_p = average plastic strain of the BRB yielding portion. It is interesting to note that μ_{max} and μ_c are dependent on the yield stress of the steel core plate [7], while ε_{max} and ε_c are not, though both of the indices are non-dimensional. There are a number of studies aiming to investigate the cumulative ductility capacity of BRBs in both building and bridge engineering, and it is important to investigate which one is more suitable to fairly evaluate the cumulative ductility capacity. It was found by one of the authors [8] that ε_c is more suitable to evaluate the cumulative ductility capacity of BRBs in steel arch bridges.

To date, BRBs have been intensively investigated through both experimental and numerical studies, e.g., [4,9–13]. However, recent strong earthquakes indicate that subsequent multiple strong aftershocks such as the 2010-2011 New Zealand earthquakes and the 2016 Kumamoto earthquake, can lead to significant damage or collapse of main structures. Especially in the 2016 Kumamoto earthquake, two strong earthquakes with the highest seismic intensity (7 in Japan) occurred within several days. This warrants consideration of structural safety subjected to multiple subsequent seismic excitations. Under this circumstance, structures need to be able to sustain both the mainshock and aftershocks [14–16], since there is not enough time to retrofit damaged structures after the mainshock. Thus, higher cumulative ductility demands of BRBs are required to avoid bracing rupture due to excitation of seismic waves with long durations and strong aftershocks. Besides, a type of reduced length buckling-restrained braces [12,17], which connect common bracings with shorter BRBs, raises higher demands of both the maximum and cumulative ductility capacities for the BRB segment. Likewise, innovative applications of energy dissipation devices may also put forward higher ductility demands for BRBs [18].

In a previous study [19], a novel all-steel fish-bone shaped BRB (FB-BRB) as illustrated in Fig. 1 has been proposed. All-steel BRBs [2,7,20–23] have more stable hysteretic properties for the simple mechanical properties of steel compared with other restraining components such as mortar filled steel tubes. Besides, self-weight of an all-steel BRB is smaller than that of a conventional BRB using a mortar filled steel tube as the restraining component, and the seismic load of a structure using the all-steel BRBs can be less than the one with conventional BRBs [24]. Besides, the proposed all-steel FB-BRBs with multiple stoppers shown in Fig. 1 can achieve controlled limit strain for each segment, leading to formation of multiple necks along the core plates. For this novel deformation mechanism, the FB-BRBs can achieve high secondary stiffness, maximum ductility and cumulative ductility. Meanwhile, the FB-BRB can still sustain tensile forces even when the core plate ruptures into two pieces owing to interaction of the multiple stoppers and the filling plates.

Both experimental and numerical studies have been carried out in the previous study of the authors [19], while the expected performance of the FB-BRBs has not been fully achieved due to low strength of the stoppers. These stoppers have two different functions, one is to reduce relative movement of the core and the restraining components, which is the same as that in a conventional BRB. The other function is to limit the ultimate deformation of the central segment of the core plate as illustrated in Fig. 1, through which damage can be distributed more evenly along the whole length of the core plate. In this paper, an experimental study of the FB-BRBs was carried out, where shear strength of the stoppers was increased compared with that of the previous study [19]. Eight specimens were employed to investigate effects of main geometrical and mechanical design parameters on seismic performance and failure mechanism of the FB-BRBs. The experimental results indicate stable hysteretic properties and superior maximum ductility and cumulative ductility of the proposed FB-BRBs. The optimal values for the main design parameters were also obtained through the experimental study.

2. Experimental program

2.1. Characteristics of FB-BRB

For mild steel, a typical load-displacement curve of a tension coupon illustrated in Fig. 2 indicates that post-necking deformation takes a substantial portion of the elongation of ductile metal. However, the post-necking deformation capacity of mild steel cannot be fully developed in a conventional BRB due to local deformation concentration at a single necked region. An approach to fully utilize the post-necking deformation capacity is to make necking deformation develop at multiple locations. The newly proposed FB-BRBs have several pairs of stoppers as shown in Fig. 1, and the stoppers will contact with the filling plates shown in the figure and restrain the ultimate tensile deformation at the central segment. This mechanism will lead to occurrence of necks at both the central and end segments of the fish-bone shaped core plate, and the post-necking deformation capacity of the

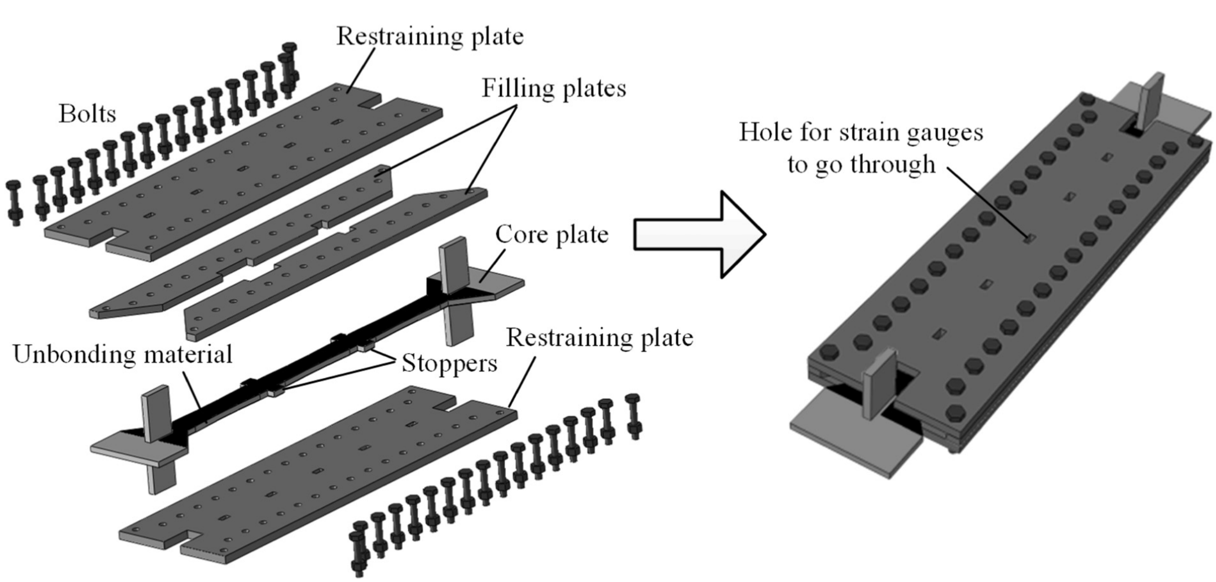

Fig. 1. Components of FB-BRB.