Engineering Structures 138 (2017) 105–119

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Development of a novel high-performance all-steel fish-bone shaped buckling-restrained brace

Liang-Jiu Jia [a], Hanbin Ge [b,*], Rikuya Maruyama [b], Kazuki Shinohara [b]

[a] Research Institute of Structural Engineering and Disaster Reduction, Tongji Univ., Shanghai 200092, China
[b] Dept. of Civil Eng., Meijo Univ., Nagoya 468-8502, Japan

ARTICLE INFO

Article history:
Received 2 February 2015
Revised 24 November 2016
Accepted 2 February 2017

Keywords:
Bucking-restrained brace
All-steel
Fish-bone
Seismic
Cyclic

ABSTRACT

Based on investigation of recent strong earthquakes, there is a potential that BRBs may rupture during a strong earthquake or subsequent repeated aftershocks. This study aims to propose a novel type of light-weighted all-steel dismountable BRB with fish-bone shaped core plate, which is termed FB-BRB in this paper. The FB-BRB consists of a core plate, two filling plates, two restraining plates and unbonding material. Deformation capacity of the proposed FB-BRB is to be maximized by generating several necking locations at the core plate, and details to avoid strain concentration at stoppers are also proposed. Experimental study is carried out using four scaled specimens with different configurations. Favorable seismic performance is obtained through comparison with that of a conventional BRB. The failure mechanisms of the newly proposed FB-BRBs are also further verified through numerical study using a combination of a ductile fracture model and a cyclic plasticity model, where further improvement is required to fully achieve the expected deformation mechanism.

1. Introduction

Buckling-restrained braces (BRBs) have been increasingly employed in building and bridge structures since the 1970s when BRBs, e.g., [1–4], were first developed in Japan. Applications of BRBs in structural engineering have been approved by more and more countries, especially after several strong earthquakes in recent decades, such as the 1994 Northridge earthquake [5,6], the 1995 Kobe earthquake [7], the 1999 Chi-Chi earthquake [8], the 2008 Wenchuan earthquake [9] and the 2011 Tohoku earthquake [10].

Two indices are generally employed to evaluate ductility capacities of BRBs, i.e., a maximum ductility index, $\mu_{\max}$, and a cumulative ductility index, μ_c. The two can be obtained using the following formulae

$$\mu_{\max} = \frac{\Delta_{\max}}{\Delta_y} \tag{1}$$

$$\mu_c = \frac{\sum \Delta_p}{\Delta_y} \tag{2}$$

where $\Delta_{\max}$ = BRB maximum deformation; Δ_y = BRB yield deformation; $\sum \Delta_p$ = accumulated BRB plastic deformation. These variables are all calculated for the yielding portion of the core plate.

According to a number of experimental and analytical studies, the maximum ductility demand, $\mu_{\max}$, for buckling-restrained braced frames (BRBFs) under a seismic input with a 2% exceedance probability in 50 years in the US, ranges from 20 to 25 [11]. Based on available experimental results to date, e.g., [12–19], there are a number of BRBs which cannot meet the maximum ductility demand of a BRBF. The cumulative ductility index, μ_c, of a BRBF is required to be larger than 200 in the US design code [20]. It has been found that the required cumulative ductility of 200 can be readily achieved for BRBFs [11]. The maximum ductility demands for BRBs employed in steel arch bridges are close to those a BRBF building. When a material with a yield stress of 235 MPa is employed for the core plate, the seismic demanded maximum average elongation of a BRB in an arch bridge is around 3%, corresponding to a maximum ductility index of 26. Meanwhile, the corresponding cumulative ductility demand is around 193 [21]. A ductility capacity lower than the demand, will lead to failure of the BRBs due to either buckling or rupture of the core plate during a strong earthquake. Besides, strong aftershocks following a strong earthquake were observed in recent years [21,22], and higher ductility demands are required for this type of seismic waves with long durations and strong aftershocks.

---

* Corresponding author.
E-mail addresses: lj_jia@tongji.edu.cn (L.-J. Jia), gehanbin@meijo-u.ac.jp (H. Ge).

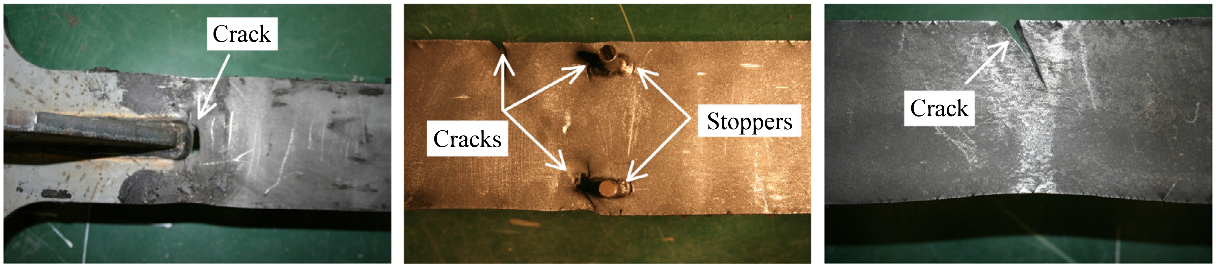
http://dx.doi.org/10.1016/j.engstruct.2017.02.006
0141-0296/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

a	initial imperfection at the mid-length of a BRB
b_c	width of the core plate
b_s	width at root of the stopper
CID	cumulative inelastic deformation
D	half of the reduced size at mid-width of the core plate
d	gap between the core plate and the restraining plate
d_0	gap between the core plate and the filling plate
E	Young's modulus
E_s	allowable maximum elongation of each segment
$F_{c,\,i}$	cross sectional total force of the i-th segment of core plate
$F_{c,\,i+1}$	cross sectional total force of the $(i+1)$-th segment of core plate
F_s	shear force sustained by a single branch of stoppers
e	eccentricity of the compressive force of the core plate
L	length of the yielding portion
M_y^R	yield moment of the restraining plate
P_E^R	buckling load of the restraining plate
P_y	yield load of yielding portion of the core plate
P_u	peak load of a coupon
S	number of stoppers at one side of the core plate
t	thickness of the core plate
$\Delta_{\max}$	maximum deformation of a BRB
Δ_y	yield deformation of a BRB
δ	elongation of a material
δ_u	deformation at instant of peak load of a coupon
$\delta_{0.95P_u}$	deformation at instant when P_u decreases by 5%
$\delta_{\max}$	maximum deformation of a coupon
ε_p	average plastic strain of the yielding portion
η_s	stopper strength index
μ_c	cumulative ductility index
$\mu_{\max}$	maximum ductility index
ν_F	index to control global buckling of a BRB
σ_y	yield strength of a material
σ_t	tensile strength of a material
τ_y	yield shear stress of a material
ΣE_p	cumulative plastic energy dissipation
$\sum \Delta_p$	cumulative plastic deformation

Typical requirements of a BRB include [23]: (1) stable hysteretic characteristic and high energy absorption capacities; (2) large deformation capacities under both compression and tension; (3) high ductile fracture-resistant properties of the core plate under a small number of loading cycles with large plastic strain amplitudes; (4) simple and low-cost fabrication and construction (e.g., connection details); (5) high low-cycle fatigue properties; (6) good weathering properties; (7) ease of replacement or no need to be replaced during service life. A number of all-steel BRBs with large maximum ductility capacity and cumulative ductility capacity, e.g., [24–35], have been developed. Compared with BRBs with mortar filled tubes as restraining components, all-steel BRBs have more stable hysteretic properties owing to high manufacturing accuracy and reliable mechanical properties of steel. Besides, compared all-steel BRBs with mortar filled steel tube type BRBs, the mass of the restraining components can be reduced by around 40%. Meanwhile, it should be noted that welding within the core can lead to poor low-cycle fatigue property compared with that of all-steel BRBs with non-welded core, e.g., [35].

Stoppers [24,25] are also employed to ensure that the restraining plates move simultaneously with the core plate, and to prevent premature local buckling at the transition parts close to the connections. A number of experimental studies on all-steel BRBs with stoppers are experimentally investigated. Typical failure modes reported in previous studies (see Fig. 1 [36]) include: (1) cracking at the weld toe of the stiffener-to-core-plate joint due to poor fracture-resistant capacity under cyclic loading; (2) cracking at the weld toe of the stopper-to-core-plate joint; (3) cracking at base metal of the core plate; (4) local buckling at the transition portion of the core plate due to large unrestrained length of the core plate; (5) local buckling of the restraining plate; (6) global buckling; (7) local buckling of the restraining plates. Local buckling at the transition part is not a problem if the maximum ductility demand is below a certain value, e.g., 3%, where the premise is that the details at the transition part are well designed. For a restraining plate with a large width-to-thickness ratio, local buckling of the restraining plate can occur under compression. This failure mode can be avoided by specifying a limit value for the width-to-thickness ratio of the restraining plate. Global buckling is related with the slenderness ratio of the whole BRB cross section. Likewise, global buckling of the whole member can be avoided by specifying the limit value of the slenderness ratio of the whole BRB cross section. Meanwhile, the aforementioned failure modes (4)–(6) are all correlated with the maximum ductility of a conventional BRB. The maximum compressive force commonly increases as the maximum ductility increases, and a large maximum ductility corresponds to a higher demand on both the local and global buckling loads. Utilizing the stoppers can greatly improve the local buckling load of the transition part, since it can reduce the unrestrained length of the transition part at the instant when the deformation changes from



(a) Weld toe of stiffener-to-core-plate joint

(b) Core plate and neighborhood of stoppers

(c) Cracking at the core plate

Fig. 1. Several typical failure modes of conventional all-steel buckling-restrained braces.