Journal of Constructional Steel Research 144 (2018) 21–39

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Numerical investigations on elastic buckling and hysteretic behavior of steel angles assembled buckling-restrained braces

Jing-Zhong Tong *, Yan-Lin Guo

Department of Civil Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 10 January 2018
Accepted 14 January 2018
Available online xxxx

Keywords:
Steel angles assembled
Buckling-restrained braces
Elastic buckling behavior
Hysteretic behavior
Finite element analysis
Restraining ratio

ABSTRACT

This paper presents a numerical investigation on elastic buckling and hysteretic behavior of a steel angles assembled buckling-restrained brace (SAA-BRB). The SAA-BRB is composed of a cruciform-sectional steel core encased by an external restraining system, which consists of four steel angles connected together by high-strength bolts and spacers. It is found that the SAA-BRB may fail in a global buckling mode or in a local buckling mode. In order to predict the global and local buckling behavior of SAA-BRBs, two design parameters: the restraining ratio and segment restraining ratio are proposed. To determine these two design parameters, a simplified theoretical model of SAA-BRBs and an accurate finite element (FE) model are used to investigate the global and local elastic buckling behaviors of SAA-BRBs. Based on more than 500 FE results, explicit expressions of the restraining ratio and segment restraining ratio are obtained and validated to be sufficiently accurate for practical design applications. In addition, 20 refined FE models considering material and geometrical nonlinearities are used to carry out parametric studies for comprehensively investigating the hysteretic behavior of SAA-BRBs. Finally, the following design recommendations for fix-ended SAA-BRBs are proposed: (1) the restraining ratio should be >2.2 to prevent a SAA-BRB from the global buckling failure, and (2) the segment restraining ratio should be >6.0 to prevent a SAA-BRB from the local buckling failure.

1. Introduction

Buckling-restrained braces (BRBs) were proposed and studied firstly by Fujimoto et al. [1,2] in late 1980s. In recent years, BRBs have been widely used in high rise buildings, serving as lateral force resisting and energy dissipating members under severe earthquakes [3]. A BRB is commonly composed of a steel core encased by the external restraining system. In practical structures, the core of a BRB carries the axial load transmitted from adjacent beams and columns of the frame structure, while the external restraining system restrains the lateral deformation of the core to prevent it from overall buckling under compression. Therefore, a BRB can achieve its full-sectional yield load of the core under compression without overall buckling [4].

In conventional BRBs, steel cores are typically encased by concrete-filled steel tubes (CFSTs), and a layer of unbonding material is usually installed along the core/restraining system interfaces to prevent the transmission of axial forces between them and to accommodate the lateral expansion of the core under compression [4–9]. However, during the application of BRBs encased by CFSTs, engineers often encountered some difficulties with the concrete when fabricating the BRB members. In order to overcome the difficulties and to reduce the self-weight of BRB members, all-steel BRBs were developed and studied by numerous researchers [10–22] in recent years. Since both the core and restraining system of all-steel BRBs are made in factories, their geometrical dimensions can be accurately controlled. In addition, an air gap is commonly maintained between the core and the restraining system in a BRB member instead of unbonding material and so it is quite convenient to fabricate and install the BRB member.

More recently, some types of assembled BRBs with their restraining systems assembled by high-strength bolts were proposed and investigated [8,23–26]. Among them, Tremblay et al. [8] proposed an assembled BRB consisting of two identical restraining members formed by a rectangular steel tube welded on a steel plate. Chou and Chen [23] developed a sandwiched BRB in which two identical restraining members were formed by welding a steel channel to a flat plate and then connected by bolts. Usami et al. [24] developed a double T-shaped steels assembled BRB. Genna and Gelfi [25,26] proposed an assembled BRB encased by two stiffened steel channels connected by high-strength bolts.

In this paper, a new assembled BRB: the steel angles assembled BRB (SAA-BRB) shown in Fig. 1 is investigated, which is similar but different to the BRB described in [27]. A SAA-BRB consists of a cruciform-sectional steel core and a restraining system composed of four steel angles assembled by high-strength bolts. The bolts are discretely distributed in the

* Corresponding author.
E-mail addresses: tjz13@mails.tsinghua.edu.cn (J.-Z. Tong), gyl@tsinghua.edu.cn (Y.-L. Guo).

https://doi.org/10.1016/j.jcsr.2018.01.015
0143-974X/

Nomenclature

Symbol	Description
A_1	Cross-sectional area of a single steel angle
A_b	Equivalent cross-sectional area of the batten plate
A_c	Cross-sectional area of the core
A_0	Cross-sectional area of the restraining system
b	Distance between $x_1 - x_1$ axes of adjacent steel angles
b_a	Width of the steel angle
b_c	Width of the core
b_s	Width of the spacer
E	Young's modulus
f_{yc}	Yield stress of the core
f_{yr}	Yield stress of the restraining system
g	Gap size between the core and restraining system on each side
I_0	Moment of inertia of the restraining system regarding as uniform cross-section
I_1	Moment of inertia of a single steel angle about $x_1 - x_1$ axis
I_1'	Moment of inertia of a single steel angle about $x_1'-x_1'$ axis
I_b	Equivalent moment of inertia of the batten plate
I_c	Moment of inertia of the core
l	Length of the SAA-BRB
l_1	Longitudinal bolt spacing
l_0	Length of the restraining system
N_b	Number of bolted sections
$P_{cr,\ c}$	Euler buckling load of the core
$P_{cr,\ l}$	Elastic buckling load of a single steel angle segment between adjacent bolts
$P_{cr,\ r}$	Elastic buckling load of the restraining system considering reduction
$P_{cr,\ 0}$	Euler buckling load of the restraining system regarding as uniform cross-section
$P_{cr,\ m}$	Elastic buckling load of the SAA-BRB
$P_{\max}$	Maximum compressive load of the SAA-BRB
P_y	Axial yield load of the core
t_a	Thickness of the steel angle
t_c	Thickness of each of the flange of the core
t_s	Thickness of the spacer
β	Equivalent batten-to-chord rigidity ratio
γ	Unit shear angle
ζ	Restraining ratio
ζ_1	Segment restraining ratio
η	Magnification factor of local elastic buckling of a single steel angle segment
λ_0	Slenderness ratio of the restraining system regarding as uniform cross-section
λ_1	Slenderness ratio of a segment of single chord member between adjacent batten plates
λ_c	Slenderness ratio of the core
λ_r	Equivalent slenderness ratio of the restraining system considering reduction
ω	Reduction factor of global elastic buckling load of the restraining system

longitudinal direction of a SAA-BRB and four bolts are installed in each of the bolted sections; spacers are installed between adjacent steel angles with holes for the high-strength bolts to pass through. The core is enhanced by increasing its cross-section at both ends to prevent it from local failure. In addition, the width-to-thickness ratio b_c/t_c of each of the flanges of the core is designed to ensure that the slenderness ratio of the core λ_c is greater than $5.07b_c/t_c$ to prevent the torsional buckling failure of the SAA-BRB [28]. The SAA-BRB possesses the characteristics of both all-steel and assembled BRBs and has some advantages over common BRBs. Firstly, similar to other types of all-steel BRBs, there is no need to cast concrete between the core and restraining system during fabrication of SAA-BRBs and their self-weights are then reduced significantly, leading to an economic design of BRB members. Secondly, the distance of adjacent steel angles could be adjusted by simply changing the thickness of spacers installed between them, leading to flexible design and construction in practice. Finally, after severe earthquakes, the damaged steel core can be replaced by recycling the restraining system, since the restraining system of a SAA-BRB is assembled by high-strength bolts and it is possible to conveniently disassemble the restraining system.

Recently, sub-assemblage tests of the SAA-BRBs involving seven specimens were performed by Guo et al. [29] as shown in Fig. 2. The specimens exhibited stable hysteretic responses and satisfied the requirement of cumulative inelastic deformations specified in AISC seismic provisions [30], indicating that well designed SAA-BRBs are suitable for practical applications as energy-dissipating members.

2. Global and local buckling failure of SAA-BRBs

2.1. Global buckling failure of a SAA-BRB associated with its restraining ratio

In designing a BRB, its global buckling should be prevented before its steel core reaches a full cross-sectional yield load. This could be accomplished by increasing restraining effect of the restraining system encasing the steel core. Global buckling failure of BRBs and its prevention were widely studied by numerous researchers [10–12,24,31–33]. In order to evaluate the restraining effect of a restraining system on the yielded core, and to further predict the global buckling behavior of a BRB, a restraining ratio denoted by ζ was proposed by Fujimoto et al. [1] as the ratio of the global elastic buckling load of the BRB to the yield load of its core.

In calculating the global elastic buckling load of a BRB under axially compressive load, a lateral contact force is assumed to act along the core/restraining system interfaces (Fig. 3). Accordingly, the elastic buckling load of a BRB is the sum of the elastic buckling loads of the core and restraining system [22] as $P_{cr,\ m} = P_{cr,\ c} + P_{cr,\ r}$. Additionally, it is considered that the tangent modulus of the core after yielding is quite small compared with its initial Young's modulus, while the restraining system commonly remains elastic during the whole loading process of a BRB. Hence the contribution of the core in the global elastic buckling load of the whole member could be ignored in defining the restraining ratio of a BRB. Consequently, the restraining ratio ζ is commonly simplified to the ratio of the global elastic buckling load of the restraining system $P_{cr,r}$ to the yield load of the core P_y as

$$\zeta = \frac{P_{cr,r}}{P_y} \tag{1}$$

where the global elastic buckling load $P_{cr,r}$ is calculated by applying a virtual axially compressive load to the restraining system and treating it as an axially compressed column [34].

It is known that a common BRB is formed by a steel core encased by a uniform-sectional restraining system. Hence, for a common BRB, the global elastic buckling load of the restraining system $P_{cr,0}$ could be calculated by using its Euler buckling load as

$$P_{cr,0} = \frac{\pi^2 EI_0}{l_0^2} = \frac{\pi^2 EA_0}{\lambda_0^2} \tag{2}$$