Cyclic experiments and global buckling design of steel-angle-assembled buckling-restrained braces

Jing-Zhong Tong¹,² · En-Yuan Zhang¹ · Yan-Lin Guo² · Chao-Qun Yu¹

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Abstract
Compared with traditional buckling-restrained brace (BRB), the steel-angle-assembled buckling-restrained brace (SAA-BRB) is an innovative BRB with light-weight, accurate control of the geometrical dimensions, easy installation, and convenient disassembly. The SAA-BRB comprises an external restraining system and a cruciform-sectional inner core. Four steel angles assemble the external restraining system with the connection of high-strength bolts, and the spacers are installed between the inner core and the restraining system. In this study, the hysteretic behavior of SAA-BRB was investigated by experiments and finite element (FE) simulations. Firstly, three SAA-BRB specimens with different restraining ratios were tested under cyclic loads to investigate the hysteretic performance. It was found that all specimens exhibited stable responses and satisfactory energy-dissipating capabilities during the whole loading process. Then, a refined FE model was established, and the experiments verified its validity in predicting the hysteretic responses of SAA-BRB. Moreover, based on the yielding criteria of the outmost fiber for the restraining member section, a design formula for the restraining ratio requirements to avoid global buckling of the SAA-BRB was deduced. Finally, extensive parametric analysis was conducted to verify the accuracy of the design formula by changing the geometric dimensions (the restraining ratio) of models. It was found that the proposed formula for the restraining ratio requirement could lead to a conservative prediction with reasonable accuracy, thus providing valuable references for the global buckling design of SAA-BRBs in engineering practice.

Keywords Buckling-restrained braces · Hysteretic behavior · Cyclic experiments · Numerical analysis · Restraining ratio · Global buckling design

List of symbols

| Symbol | Description |
|--------|-------------|
| A₁     | Cross-sectional area of a single steel angle |
| A₀     | Cross-sectional area of the external restraining system |
| Aₑ     | Cross-sectional area of the steel core |
| b      | Width of yield segment of the inner core |

Jing-Zhong Tong
tongjz@zju.edu.cn

¹ Institute of Advanced Engineering Structures, Zhejiang University, Hangzhou 310058, China
² Department of Civil Engineering, Tsinghua University, Beijing 100084, China
\( b_a \) Length of the steel angle flange
\( b_1 \) Width of strengthened segment of the inner core
\( E \) Young's modulus
\( f_{yr} \) Yield stress of the external restraining system
\( f_{yc} \) Yield stress of the inner steel core
\( F_y \) Yield load of the specimen
\( F_{\text{max}} \) Maximum load of the specimen
\( g \) Gap size between the steel core and restraining system
\( h_{ar} \) Distance between the edge of restraining system and the bolts circle center
\( H \) Height of frame connected with the BRB
\( I_0 \) Moment of inertia regarding the external restraining system as a whole
\( I_1 \) Moment of inertia of a single steel angle
\( K_i \) Axial secant stiffness
\( l \) Length of SAA-BRB
\( l_0 \) Length of the restraining system
\( l_y \) Length of yield segment of the inner core
\( l_u \) Length of unrestrained segment of the inner core
\( l_t \) Length of transition segment of the inner core
\( l_s \) Length of strengthened segment of the inner core
\( \Delta_l_y \) Axial deformation of the BRB
\( \Delta_y \) Yield displacement of the specimen
\( \Delta_{\text{max}} \) Maximum displacement of the specimen
\( +\Delta_i \) Displacement corresponding to tensile peak point at i-th hysteretic cycle
\( -\Delta_i \) Displacement corresponding to compressive peak point at i-th hysteretic cycle
\( l_1 \) Bolts spacing along the longitudinal direction
\( L \) Length of frame connected with BRB
\( M_{\text{max}} \) Maximum bending moment at mid-span of the restraining system
\( P_{\text{cr}} \) Euler buckling load of BRB
\( P_{\text{cr},0} \) Euler buckling load of the external restraining system of ordinary BRB
\( P_{\text{cr},c} \) Euler buckling load of the inner core
\( P_{\text{cr},r} \) Euler buckling load of the external restraining system of SAA-BRB
\( P_y \) Yield load of the inner core
\( P_c_{\text{max}} \) Load corresponding to compressive peak point of the hysteretic curve
\( P_{\text{max}} \) Load corresponding to tensile peak point of the hysteretic curve
\( +P_i \) Load corresponding to tensile peak point at i-th hysteretic cycle
\( -P_i \) Load corresponding to compressive peak point at i-th hysteretic cycle
\( S_{\text{(ABC+CDA)}} \) Area enclosed by a single hysteretic curve and the abscissa
\( S_{\text{(OBE+ODF)}} \) Triangle area enclosed by a dotted line and the abscissa
\( t \) Thickness of the inner core
\( t_a \) Thickness of steel angle
\( v_0 \) Amplitude of the initial geometrical imperfection of the SAA-BRB
\( v_{\text{max}} \) Lateral maximum deformation at mid-span of the restraining system
\( W \) Plastic section modulus of the external restraining system of SAA-BRB
\( \omega \) Reduction factor of global buckling load of external restraining system
\( \zeta \) Restraining ratio
\( [\zeta] \) Restraining ratio requirements
\( \lambda_0 \) Slenderness ratio regarding the external restraining system as a whole
\( \lambda_i \) Slenderness ratio of a segment of single chord member
σ_{max}  Maximum normal stress of the external restraining system  
λ_c  Slenderness ratio of the inner core  
α  Angle between the BRB and its connected frame beam  
[ε_c]  Maximum axial strain requirement of the BRB  
φ  Ratio of the inner core yield segment length to BRB length  
β  Compression strength adjustment factor  
ξ_{eq}  Equivalent viscous damping ratio

1 Introduction

As a high-performance member with excellent lateral resistance and energy dissipation capacity, buckling-restrained brace (BRB) has been widely used in engineering practice in many countries such as Japan, the US, and China over the years (Kiggins and Uang 2006; Tremblay et al. 2006; Zhao et al. 2017). Generally, the BRB is composed of an inner steel core encased by an external restraining system. The inner core is used to bear the axial load, and the external member is used to limit the lateral displacement of the inner core to prevent it from global buckling (Tong et al. 2020). In the design of BRB, the inner core should reach its full-sectional yield load without undergoing global buckling/local failure mode, ensuring the excellent load-carrying performance and energy-dissipating capacity of BRBs (Black et al. 2004; Eryasar and Topkaya 2010; Kiggins and Uang 2006; Tong and Guo 2018; Rahnavard et al. 2018; Atasever et al. 2020).

Under regular use or minor earthquakes, BRB can provide sufficient lateral stiffness and horizontal bearing capacity for the frame structure as common braces, and the inner core is in an elastic working state. Under the action of severe earthquakes, BRB can fully develop its plasticity and energy dissipation capacity, reducing damage to the main frame structure (Ariyaratana and Fahnestock 2011; Takeuchi et al. 2010; Zhao et al. 2013; Sutcu et al. 2020; Saingam et al. 2020). Therefore, the application of BRB not only avoids the global buckling of ordinary braces under severe earthquakes, but achieves excellent energy-dissipating performance to protect the frame structure (Shi et al. 2018; Naghavi et al. 2019).

The concept of BRB was first proposed by Yoshino and Karino (1971). In that study, a member with steel plates embedded in reinforced concrete shear walls was proposed. Its working principle is to restrain the buckling of the embedded steel plate through the external concrete wall panel. However, this is not conductive to the material utilization because only the diagonal strip-shaped area of the concrete wall can directly limit the lateral deformation of the embedded steel plate. In this consideration, BRB has gradually evolved into a type in which a slender external restraining system constrains the inner core to further improve the utilization of material. In early development stage of this type of BRBs, a typical restraining member is composed of concrete-filled steel tube or reinforced concrete (Mochizuki et al. 1979; Nagao et al. 1992). Since the restraining system is used to limit the lateral deformation of the inner core, a thin layer of unbonded material should be installed at the interface between the inner core and its surrounding concrete to avoid axial force transmission (Fujimoto et al. 1990; Ju et al. 2009; Palazzo et al. 2009; Guo et al. 2015). However, complex construction procedures caused by wet concrete work, heavy self-weight and inconvenient disassembly result in difficulties when repairing the BRB after an earthquake (Ju et al. 2009; Shi et al. 2018). To solve these problems, researchers proposed BRBs with all-steel composition and conducted experimental and numerical studies (Guo et al. 2016; Guo et al. 2017a, b; Hosseinzadeh and Mohebi 2016; Jia et al. 2020).
The all-steel BRB is mainly characterized by a steel core with a circular section or H-section and a restraining member of a circular or square steel tube. Due to its all-steel composition, there is no need for unbonded material at the interface between the inner core and the restraining member as an air gap could be precisely controlled during its fabrication (Guo et al. 2017a; Jia et al. 2017; Mirtaheri et al. 2017). Besides, the self-weight of all-steel BRB is significantly reduced compared with the traditional BRB composed of an inner steel core with the encasement of concrete-filled steel tube. Furthermore, to satisfy the requirements of high-rise buildings or long-span structures with popularity in recent years, assembled BRBs with bolt-connected restraining systems were proposed and investigated by numerous researchers (Chou and Chen 2010; Dehghani and Tremblay 2018; Ding 2014; Guo et al. 2018; Jiang et al. 2017; Metelli et al. 2016; Tong and Guo 2018; Chou et al. 2019). Chou and Chen (2010) developed a sandwiched assembled BRB with an inner core encased by two identical restraining members connected with high-strength bolts, and four BRB specimens were tested to investigate the load-carrying performance. Dehghani and Tremblay (2018) proposed an all-steel assembled BRB composed of a flat plate core and a rectangular restraining member with a hollow steel section. The stable seismic performance and high post-yield stiffness of this BRB were examined by experiments. Jiang et al. (2017) developed a pinned double-rectangular tube assembled BRB, which exhibited satisfactory energy-dissipating performance under repeated axial-tension loading. Guo et al. (2018) proposed an assembled BRB in which the restraining member consists of four steel channels assembled by bolts. A FE model that could well predict the hysteretic responses was established and a design procedure was proposed subsequently. For assembled BRBs, the external restraining system generally includes multiple components connected by high-strength bolts. The advantages of assembled BRB include: (1) the fabrication of BRB with the bolt connection is convenient and quick; (2) the BRB can be easily disassembled, reducing the difficulty in transportation and erection; (3) the damaged core can be easily replaced in the post-earthquake structure due to the feature of easy disassembling. It should be noted that the discrete arrangement of the connecting bolts will weaken the rigidity of the restraining member in the design of assembled BRBs.

In this paper, an alternative type of assembled BRB called steel-angle-assembled BRB (SAA-BRB) was studied. The SAA-BRB consists of a cruciform-sectional steel core and a restraining system composed of four steel angles. The cyclic loading experiment was carried out on three specimens to investigate the load-carrying performance and hysteretic response of SAA-BRB. Besides, a finite element (FE) model of SAA-BRB was established, and the comparison against experimental results verified the feasibility of the model. Moreover, the theoretical design formula with restraining ratio requirements to prevent SAA-BRB from global buckling was derived. Finally, extensive FE simulations were performed to validate the proposed design formula.

2 Cyclic experiments

2.1 Experimental specimens

Three SAA-BRB specimens were designed to experimentally investigate their hysteretic responses. Figure 1 shows the construction details of SAA-BRB specimens, which consists of an inner steel core with a uniform cruciform-section and a restraining system as
well as spacers. The external restraining system is composed of four steel angles assembled by high-strength bolts (M16). The spacers with holes for the bolts to pass through are installed between the steel angles. The inner core can be divided into yield segment and unrestrained segment composed of a transition segment and a strengthened segment along its longitudinal direction. The unrestrained segment of the core was enhanced at both ends by expanding its cross-sectional size, and it was welded with a flange to prevent it from local buckling. Besides, the stiffened plates were set at the end of each steel angle along the longitudinal direction to enhance the integrity of the external restraining member. According to Chinese design code GB50017 (GB 2017), the slenderness ratio of the core $\lambda_c$ should be greater than $5.07b/t$ to prevent the torsional buckling failure of SAA-BRB. Additionally, the stoppers (i.e. displacement limitation fastener) were designed and arranged on each side of the mid-span of the core by welding to inhibit the restraining system from sliding longitudinally along the core. It should be noted that the cruciform inner core is welded by three steel plates according to the Chinese code GB50661 (GB 2011). Figure 2 shows the fabrication of cruciform inner core. In the welding process, a full penetration groove weld was used. The groove form was K-shaped, the joint form was a cross-shaped, and the weld form was a butt weld. In

Fig. 1 Construction details of SAA-BRB specimens

Fig. 2 Fabrication of cruciform inner core
addition, the grinding to flat after welding was implemented to prevent the corners of the steel angles from clashing.

It is well known that a restraining ratio $\zeta$ used to design the BRB is defined by the ratio of the Euler buckling load of the restraining system to that of the inner steel core. Therefore, geometrical configurations of the inner core and restraining system such as cross-sections area and length are the reflections of the restraining ratio on the size of BRB. The design parameters of each specimen are tabulated in Table 1. For all specimens, SAA-BRB length, $l$, and restraining system length, $l_0$, were 2400 mm and 2100 mm, respectively. The steel angle width $b_a$ of Specimen S-1 was 80 mm, and those of Specimens S-2 and S-3 were 90 mm. Steel angle thickness $t_a$ was 6 mm for each specimen. The cruciform-sectional core member width, $b$, was 100 mm for Specimens S-1 and S-2 while 110 mm for Specimen S-3. Inner core thickness, $t$, was 22 mm for each specimen. It can be seen from Table 1 that the restraining ratios for specimens S-1, S-2 and S-3 are 1.86, 2.47 and 2.22, respectively. As a key parameter for designing the BRB, the value of $\zeta$ is expected to be greater than the lower limit of the restraining ratio $[\zeta]$ to ensure that the retraining system has sufficient stiffness and that the BRB does not undergo global buckling. The theoretical deduction of the $[\zeta]$ will be presented in the theoretical analysis for the global buckling design of this study.

To avoid the axial load sustained by the inner core being transmitted to the restraining system, hard rubbers with a thickness of 1.2 mm were installed between the steel core and four steel angles. The spacer thickness of all specimens was 25 mm, and the spacer widths in the transverse direction of the cross-section and the longitudinal direction were 48 mm and 42 mm, respectively.

### 2.2 Material properties

The material tests on the steel utilized for the components (inner steel core and steel angle) were conducted according to the Chinese code GB/T 288.1 (GB/T 2010), and each component has two tensile coupons to be tested. The material properties of each component were obtained by averaging the results of the two tensile coupons. Table 2 shows the measured

| Specimen no | $b$ (mm) | $b_1$ (mm) | $b_a \times t_a$ (mm) | $h_{ar}$ (mm) | $g$ (mm) | $l_0$ | $f_{yr}$ (MPa) | $f_{yc}$ (MPa) | $\zeta$ |
|-------------|---------|------------|-----------------------|--------------|---------|-------|----------------|----------------|------|
| S-1         | 100     | 200        | 80×6                  | 25           | 1       | 2100  | 380            | 288            | 1.86 |
| S-2         | 100     | 200        | 90×6                  | 35           | 1       | 2100  | 380            | 288            | 2.47 |
| S-3         | 110     | 220        | 90×6                  | 35           | 1       | 2100  | 380            | 288            | 2.22 |

| Components   | Elastic modulus (MPa) | Poisson’s ratio | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) |
|--------------|-----------------------|-----------------|----------------------|------------------------|----------------|
| Inner steel core | 1.98×10^5            | 0.3             | 288                  | 349                    | 33.5           |
| Steel angle  | 1.98×10^5            | 0.3             | 380                  | 493                    | 32.2           |
steel properties. Figure 3 shows the stress–strain curve of steel. For steel used for seismic structures, it should be aware that the elongation shall exceed 20% and the ratio of yield stress to tensile strength shall not exceed 0.85 according to the Chinese code GB50011 (GB 2010). As tabulated in Table 2, the material properties of the SAA-BRB specimens fulfil these requirements.

### 2.3 Experimental setup and loading protocol

The MTS hydraulic servo testing machine was used for applying cyclic loads. Figure 4 presents the experimental setup consisting of two reaction frames anchored to the strong floor and test specimens loaded via a 600 t actuator with an in-line load cell. At both ends of each specimen, the flange with Q345 steel plate is connected to the cross-shaped connecting plate using high-strength bolts, and the cruciform-shaped connecting plate is also connected to the actuator and the reaction frame with the connection of bolts.

As shown in Fig. 5, $H$ and $L$ respectively denote the height and length of the frame connected with BRB, $\alpha$ the angle between the BRB and the frame beam, thus the length of the BRB $l$ can be expressed as $l = \sqrt{H^2 + L^2}$. For BRB, the length of the yield segment of the core is $l_\gamma$, thus the ratio of the core yield segment length to BRB length is denoted as $\varphi = l_\gamma/l$. According to the Chinese code GB50011 (GB 2010) for seismic design of buildings, the maximum drift angle of the frame structure is $1/50$ under severe earthquakes. Hence, the maximum axial deformation of the inner core can be expressed as $\Delta l_\gamma = H\cos\alpha/50$. In engineering practice, axial deformation mainly occurs in the yield
segment of the core due to the unrestrained segment of the core being enhanced by increasing its sectional size. Therefore, the maximum axial strain requirement $[\varepsilon_c]$ of the BRB can be expressed as Eq. (1) by assuming that the axial deformation entirely occurs in the yield segment of the core.

$$[\varepsilon_c] = \frac{\Delta l_y}{l_y} = \frac{H \cos \alpha / 50}{\varphi H / \sin \alpha} = \frac{\sin \alpha \cos \alpha}{50 \varphi}$$

Assuming that $\alpha = 45^\circ$ and $\varphi = 0.5$, it is calculated as $[\varepsilon_c] = 0.02$. Therefore, the axial strain of 2.00% was determined as the maximum strain in the loading protocol.

Prior to the standard loading process, the axial compressive load of half of the yield load calculated from the FE model was preloaded to check whether the experimental devices and measuring instruments were reliable. After that, the standard loading process, in which three loading cycles with an axial strain of 0.25%, 0.50%, 0.75%, 1.00%, 1.50%, and 2.00%, were performed successively to the specimens based on AISC provisions (AISC 2016). The axial displacement loading protocol of the standard loading process for each specimen is tabulated in Table 3. The standard cyclic loading protocol of the axial strain with respect to the cycle number for each specimen is illustrated in Fig. 6.

Fig. 5  Calculation of the maximum axial strain requirements

### Table 3  Axial displacement loading protocol

| Load step | Number of cycles | Axial strain (%) | Axial displacement (mm) |
|-----------|-----------------|-----------------|------------------------|
| 1         | 3               | ±0.25           | ±5.00                  |
| 2         | 3               | ±0.50           | ±10.00                 |
| 3         | 3               | ±0.75           | ±16.00                 |
| 4         | 3               | ±1.00           | ±21.00                 |
| 5         | 3               | ±1.50           | ±32.00                 |
| 6         | 3               | ±2.00           | ±42.00                 |
2.4 Measurement point arrangements

The measuring-point arrangements of strain gauges and out-of-plane displacement meters are presented in Fig. 7. The strain gauges were installed on the steel angles to record the axial strain. There were two measured sections: Sects. 1 and 2, and each section had eight measuring points. For displacement meters, in addition to two axial displacement meters (as shown in Fig. 4) used to examine the axial deformation, six out-of-plane displacement meters were located near the mid-span bolt sets and near the quarter points of the restraining member along the longitudinal direction.
2.5 Experimental results

2.5.1 Hysteretic curves and skeleton curves

Since the values obtained from the out-of-plane displacement meters were significantly small (close to zero), i.e., there were essentially no out-of-plane deformations. Hence, Fig. 8 shows the axial force of all specimens with respect to the axial displacement. It is shown that the hysteretic curves of the three SAA-BRB specimens maintained stable during the whole cyclic loading process, indicating that SAA-BRB has great energy-dissipating capacity under severe seismic effects. Figure 9 illustrates the deformation condition corresponding to a core strain of 2.00%. It is found that none of the specimens showed global buckling or local buckling. This is because the restraining ratio of each specimen is greater than the corresponding restraining ratio requirement. In addition, according to this loading protocol, when the SAA-BRB specimens completed three 2.00% axial strain loadings, the cumulative plastic strain would exceed the yield strain of 200 times as specified in AISC provisions (AISC 2016). Hence, the specimens were not continuing to be loaded, which prevented the core from being fractured.

Fig. 8 Hysteretic curves of specimens
The skeleton curves of specimens are depicted in Fig. 10. The displacement and load values corresponding to the yield and peak points of all specimens are shown in Table 4. When the specimens reach 2.00% axial strain, the skeleton curves still maintain increasing trends, indicating that the SAA-BRB specimens have a cyclic effect and great ductility under axial cyclic loading. Hence, it is conservative to take the peak point of the specimen as the last point of the skeleton curve to leave enough safety redundancy. In addition, each specimen curve has obvious inflection points, which are determined as the yield points of the specimen.

Fig. 9 Deformation condition corresponding to 2.00% axial compression strain

Fig. 10 Skeleton curves of specimens
2.5.2 Equivalent viscous damping ratio

Figure 11 illustrates the equivalent viscous damping ratios of all specimens with respect to the hysteretic loop. The energy-dissipating capacity of the specimen can be quantitatively evaluated by the equivalent viscous damping ratio ($\xi_{eq}$), which can be calculated by Eq. (2). It is seen that the equivalent viscous damping ratio of all specimens generally presents an increasing trend with the increase of the hysteretic loops. Specifically, before the specimens yielded (i.e., before the specimens reached 0.25% axial strain), the values of $\xi_{eq}$ ranged from 0.20 to 0.30. As the inner core gradually consumed energy during the loading process, the values of $\xi_{eq}$ increased until they stabilized above 0.40. Moreover, the maximum equivalent viscous damping ratios of the three specimens all exceeded 0.50, demonstrating that all the SAA-BRB specimens exhibited excellent energy-dissipating capacity.

$$\xi_{eq} = \frac{1}{2\pi} \frac{S_{(ABC+CDA)}}{S_{(OBE+ODF)}}$$  \hspace{1cm} (2)

| Specimen no | Loading direction | Yield points | Peak points |
|-------------|-------------------|--------------|-------------|
|              |                   | $F_y/kN$     | $\Delta_y/mm$ | $F_{max}/kN$ | $\Delta_{max}/mm$ | $\beta$ |
| S-1         | Tension           | 1212.58      | 4.77        | 1862.36      | 41.66              | 1.06    |
|             | Compression       | −1208.38     | −4.93       | −1971.56     | −41.33             |         |
| S-2         | Tension           | 1166.98      | 4.80        | 1730.37      | 40.04              | 1.09    |
|             | Compression       | −1129.18     | −4.85       | −1884.56     | −41.91             |         |
| S-3         | Tension           | 1299.57      | 4.92        | 1916.36      | 40.38              | 1.08    |
|             | Compression       | −1267.77     | −5.13       | −2063.96     | −41.36             |         |

Fig. 11 Equivalent viscous damping ratio of specimens
in which $S_{(ABC+CDA)}$ denotes the enveloping area of the hysteretic loop curve in Fig. 12; and $S_{(OBE+ODF)}$ denotes the area of the triangles OBE and ODF in Fig. 12.

### 2.5.3 Compression strength adjustment factor

The asymmetric response under tension and compression of the SAA-BRB can be evaluated by the compression strength adjustment factor $\beta$, which is defined by Eq. (3). The larger the $\beta$, the more obvious the asymmetric response is. It is calculated that the $\beta$ values of the three SAA-BRB specimens are 1.06, 1.09, and 1.08, respectively as tabulated in Table 3. ANSI/AISC 341–16 (AISC 2016) specified that the factor $\beta$ shall exceed unity but be no greater than 1.50. Therefore, it is shown that SAA-BRB has a reasonable hysteretic response under both tension and compression.

$$\beta = \frac{P^i_{c_{\text{max}}}}{P^i_{t_{\text{max}}}}$$

in which $P^i_{c_{\text{max}}}$ and $P^i_{t_{\text{max}}}$ are the loads corresponding to the compressive and tensile peak points of the hysteretic curve, respectively.

### 2.5.4 Stiffness degradation

The stiffness degradation properties of all specimens are shown in Fig. 13. The axial stiffness degradation curve can reflect the damage history of BRB under cyclic loads. According to the Chinese code JGJ/T 101 (JGJ 2015), the secant stiffness $K_i$ is used to express the stiffness of the specimen and its calculation is shown in Eq. (4). The horizontal coordinate of Fig. 13 is the displacement corresponding to the peak point of each loop in the compressive or tensile directions. It is found that the secant stiffnesses of all specimens are basically identical at the same load step. In addition, although the axial stiffness of three SAA-BRB specimens decreased during the loading process, the rate of stiffness degradation gradually slowed down. This shows that the SAA-BRB would not lose its stiffness instantaneously during loading.

$$K_i = \frac{\pm P_i}{\pm \Delta_i}$$

in which $+P_i$ and $-P_i$ are the loads corresponding to tensile and compressive peak points of the hysteretic curve at the $i$-th cycle, respectively; $+\Delta_i$ and $-\Delta_i$ are the displacements.
corresponding to tensile and compressive peak points of the hysteretic curve at the i-th cycle, respectively.

2.5.5 Longitudinal strain of restraining system

Figure 14 shows the longitudinal strain distribution and development of the external restraining system of the three specimens. Since the external restraining system was not loaded when the inner core was under tension, the following analysis focuses on the longitudinal strain of the external restraining member for the peak compressive displacement in each loading loop. It is found that the difference between strain data of 1–1 section and 2–2 section is relatively small, hence the data of 2–2 section is selected for strain analysis. Taking the average value of a pair of strain data at the same height as the vertical coordinate and the height of the cross-section as the horizontal coordinate, the distribution of the longitudinal strains on the cross-section is plotted. It can be seen from Fig. 14 that the major bending direction of SAA-BRB specimens is the up and down direction. Moreover, it is found that all strain values were less than the yield strain (i.e., 1670 με for Q345 steel), indicating a good consistency with the stable load-carrying capacities of these specimens during the loading process as shown in Fig. 9. Theoretically, the strain distribution of the cross-section of the external restraining member is strictly linear if the restraining system can be regarded as a fully flexural member. However, the sectional strain distribution of each SAA-BRB specimen depicted in Fig. 14 shows that the linearity is violated.

![Fig. 13 Curves of axial secant stiffness degradation](image)

![Fig. 14 Distribution and development of longitudinal strains in restraining system](image)
This indicates that significant shear deformation exists in the restraining system and the plane-section assumption is inappropriate for the SAA-BRB. This is mainly caused by the discrete layout of the connecting bolts in the restraining system. When the inner core was under compression and developed multi-wave buckling mode, lateral thrust effect existed between the core and restraining system, thus causing friction along their interface. Hence, part of the axial load of the inner core was transmitted to the restraining system. This explains that the measured compressive strain is larger than tensile strain in the two measuring-points which are symmetrical to the midline of the cross-section of each specimen.

3 FE model and validation

3.1 Establishment of hysteretic model

In this section, the hysteretic behavior of the SAA-BRBs is simulated with Abaqus by establishing a refined FE model. The refined FE model is depicted in Fig. 15. Generally, solid elements can be used to model almost any shape, while shell elements are often used to simulate thin-walled components with small width-to-thickness. Compared to other components, the width-to-thickness ratio of steel angles is significantly small. Hence, the four-node shell element (S4R) was used to simulate the steel angles, and the eight-node solid element (C3D8R) was used to simulate the inner core, spacer and high-strength bolts. It is pointed out that the high-strength bolts were set as infinitely rigid in the FE model because of their sufficient stiffness during the cyclic loading process of the experiments. Additionally, an air gap with a thickness of 1.0 mm on the surface of the inner core was set to ensure that the axial load transmission between the core and external restraining member was prevented. The specific geometric parameters of the FE model are identical to those of the specimens.

In elastoplastic FE analyses, both geometric nonlinearity and material nonlinearity are considered. It is known that the material nonlinear constitutive relationship mainly consists of yielding and strengthening criteria. In modelling the hysteretic behavior of SAA-BRBs, the von Mises yielding criterion was considered in the material, and a combined isotropic and kinematic hardening model was selected as the strengthening criterion to consider the cyclic effect shown in the experimental results. The yield stress values of the inner core

Fig. 15 FE model for hysteretic analysis
and steel angles were 288 MPa and 380 MPa, respectively. It should be noted that these values were the same as the corresponding data tabulated in Table 1. Based on the suggestion of Guo et al. (2017c), the parameters described below were well validated by the previous experiments for SAA-BRB. For isotropic hardening, a rate factor of 4.2 and a maximum change in yield stress of $Q_\infty = 150$ MPa were used in the model. Besides, the relevant moduli and rate factors for kinematic hardening were set as $C_1 = 32$ GPa, $\gamma_1 = 300$; $C_2 = 6$ GPa, $\gamma_2 = 150$; $C_3 = 0.6$ GPa, and $\gamma_3 = 22$.

A preliminary mesh sensitivity analysis was conducted to select an appropriate mesh size since different mesh sizes have an impact on the time and accuracy of numerical computations. The approximate global mesh seed size for the steel angles and the inner core was 15 mm, while the spacer was 10 mm (It is known that the Abaqus program performs meshing by arranging mesh seeds, and the approximate global/local mesh seed size could be set in the program). Additionally, to make the numerical computation easier to converge during the analysis process, the local mesh seed size at the bolt region was optimized, which was approximately 5 mm.

For the contact behavior, the interface between the core and restraining system was simulated by hard contact along the normal direction and friction option along the tangent direction. The hard contact option allowed the interface to separate under tension but not penetrate under compression. The friction coefficient of 0.1 was adopted based on the suggestion of Chou and Chen (2010). In terms of the boundary conditions, both ends of SAA-BRB were modelled as fixed ends since the core was connected with the flange by high-strength bolts. Correspondingly, the rotational degree of freedom of the core at both ends was constrained. Additionally, an initial geometrical imperfection with a magnitude of $1/1000$ of the specimen length for the inner core was assigned to the FE model. The loading protocol was the same as that used in the experiment as listed in Table 3, except for the cycle number of each loading level, which was determined to be only one instead of three.

### 3.2 Validation of FE model

The comparison between the hysteretic curves obtained from FE simulations and experiments are illustrated in Fig. 16. It is seen that the hysteretic curves of the FE models and experiments can fit very well although there exists a remarkable difference in the initial cycle. The reasons for the difference are summarized as follows: the assembly between the components in the FE model is ideal, but the assembly is greatly affected by manual operations, physical defects and material batches in the experimental program. Hence, in the initial cycles of loading, there would inevitably be a process of eliminating the voids between the components in the test, which may lead to a remarkable gap between the FE and the experiment results; although the FE model using the combined isotropic and kinematic hardening model as the strengthening criterion can accurately predict the hysteretic response of SAA-BRB, there also may inevitably be some limitations in applying this model to simulate BRB.

Moreover, the model in the FE simulation showed the same stable load-carrying performance at the axial strain of 2.00% as the specimen in the experiment. Taking the model T-2 as an example, neither the restraining member nor the inner core was observed to undergo global buckling failure, while full cross-sectional yielding of inner core was exhibited at the axial strain of 2.00%, as depicted in Fig. 17. Therefore, the refined FE model developed by software Abaqus could precisely predict the hysteretic response of the SAA-BRB specimens under cyclic loads.
In addition, the unrestrained segment of the core remained elastic, while yielding had spread in the yield segment of the core. This further verifies the feasible design of unrestrained segment of the core by enlarging their cross-sectional size. Moreover, the maximum stress of the steel angles was far less than its yield stress of 380 MPa, indicating that the restraining system had sufficient flexural stiffness to limit the lateral deformation of the inner core.

![Image](image_url)

**Fig. 16** Comparison of experimental and numerical results of hysteretic curves

**Fig. 17** Stress distribution of model T-2 at the axial strain of 2.00%
4 Theoretical analysis for global buckling design

In this section, the formula for restraining ratio requirements of the SAA-BRB is derived. In designing BRB, a restraining ratio $\zeta$ proposed by Fujimoto et al. (1988), reflecting the restraining effect of the external restraining system on the inner core, is usually used to predict the global buckling behavior and to examine the load-carrying performance of BRBs. It is known that the restraining ratio $\zeta$ is defined as the ratio of the Euler buckling load $P_{cr}$ of BRB to the yield load $P_y$ of its inner core. The Euler buckling load $P_{cr}$ of BRB can be considered as the sum of the Euler buckling load $P_{cr,c}$ of inner core and the Euler buckling load $P_{cr,r}$ of restraining system (Guo et al. 2016). Since the restraining system remains elastic while the inner core yields during the loading process, leading to the negligible contribution of inner core in calculating the Euler buckling load $P_{cr}$ of BRB. Therefore, the restraining ratio $\zeta$ is commonly simplified as the ratio of the Euler buckling load $P_{cr,r}$ of the restraining system to the yield load $P_y$ of the inner core, as expressed by Eq. (5).

Theoretically, as long as the restraining ratio is slightly larger than unity, the cross-sectional strength of inner core can be fully utilized, thus the BRB can maintain stable without global buckling during the whole loading process. However, considering the influence of physical defects such as initial geometric imperfection, residual stress, as well as the gap between the inner core and the restraining system, the restraining ratio is required to be much larger than unity, indicating the calculation of the requirements of the restraining ratio would be relatively complicated. Through a reasonable design, the SAA-BRB will exhibit stable behavior instead of undergoing global buckling before its inner steel core reaches the full cross-sectional yielding load (Tong and Guo 2017). Although Tong and Guo (2018) have given the design suggestion about the restraining requirement of SAA-BRB, there is still a lack of a precise design formula to determine the restraining ratio as required. During the cyclic loading process, the external restraining system can be regarded as a flexural member. Therefore, the formula of the critical restraining ratio, i.e., the calculation of restraining ratio requirement of SAA-BRB, can be derived by using the yielding criteria of outmost fiber for the restraining system section as the elastic limit criterion.

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

in which $P_{cr,r}$ is the Euler buckling load regarding the restraining system as an axial loading member; $P_y$ is the yield load of the inner core.

For an ordinary BRB with an inner steel core encased by a uniform-sectional restraining member, the Euler buckling load of the restraining system can be calculated as

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

in which $E$ is the Young’s modulus of the restraining member; $A_0$ is the cross-sectional area of the restraining member and $\lambda_0$ is the slenderness ratio of the restraining member of ordinary BRB, which can be calculated by Eq. (9).

It is known that the arrangement of discretely distributed bolts in the longitudinal direction would result in a significant shear deformation of the restraining system, thus reducing the Euler buckling load. Hence, a reduction factor $\omega$ is introduced to consider the effect of shear deformation, as expressed in Eq. (7). The value of $\omega$ is closely related to the geometric dimensions of the assembled BRB and is generally smaller than unity.
For the SAA-BRB, Tong and Guo (2018) introduced the derivation of the formula for \( \omega \) through numerous FE simulations and theoretical analysis, which is expressed by Eq. (8). It should be noted that the derivation of reduction factor \( \omega \) is based on the equivalence of the restraining system into a four-chord batten column. In the equivalent relation, the four angle steels were equivalent to four chord members, and the spacers were equivalent to batten plates (Tong and Guo 2018).

\[
P_{crr} = \omega P_{c,0}
\]  
\[
\omega = \left[ 1 + \frac{\pi^2 \lambda_1^2}{12 \lambda_0^2} + 17.4 \frac{\lambda_1^{0.55}}{\lambda_0^{1.27}} \right]^{-1}
\]

in which \( \lambda_1 \) is the slenderness ratio of a single chord member between adjacent batten plates.

\[
\lambda_0 = \frac{l_0}{\sqrt{I_0/A_0}}
\]

in which \( \lambda_0 \) is the slenderness ratio regarding the external restraining system as a member with a uniform cross-section; \( l_0 \) is the length of the external restraining system; \( I_0 \) is the moment of inertia regarding the external restraining system as a whole about the \( x-x \) axis and \( A_0 \) is the cross-sectional area of the external restraining system.

\[
\lambda_1 = \frac{l_1}{\sqrt{I_1/A_1}}
\]

in which \( l_1 \) is the longitudinal spacing between adjacent high-strength bolts, which is equal to the spacing between adjacent batten plates; \( I_1 \) is the moment of inertia of a single angle about the \( x_1-x_1 \) axis, \( A_1 \) is the cross-sectional area of a single steel angle. Besides, the \( x-x \) axis for calculating the \( I_0 \) and \( x_1-x_1 \) axis for calculating the \( I_1 \) are shown in Fig. 18.

When the load reaches the value corresponding to the yield load of the inner steel core, the maximum lateral deformation \( v_{\text{max}} \) at the mid-span of the restraining system in the longitudinal direction can be expressed as (Timoshenko et al. 1962)

\[
P_{crr} = \omega P_{c,0}
\]
in which \( v_0 (= L/1000) \) is the amplitude of initial imperfection and \( g \) is the gap between the inner steel core and the restraining member.

When global buckling occurs, the maximum bending moment \( M_{\text{max}} \) at the mid-span of the restraining system can be expressed as

\[
M_{\text{max}} = P_y v_{\text{max}}
\]  

(12)

Correspondingly, the maximum stress of the restraining system can be calculated by Eq. (13). It should be aware that the plastic section modulus \( W \) is multiplied by the reduction factor \( \omega \) to express the weakening effect of discrete bolt connection.

\[
\sigma_{\text{max}} = \frac{M_{\text{max}}}{\omega W}
\]  

(13)

Based on the yielding criteria of outmost fiber for the restraining system section, the overall stability requirement of the SAA-BRB subjected to axial compressive load can be expressed as

\[
\sigma_{\text{max}} \leq f_{yr}
\]  

(14)

in which \( f_{yr} \) is the yield stress of the restraining system.

By combining Eqs. (5), (7), and (11)–(14), a calculation for a lower limit of restraining ratio \([\zeta]\) for SAA-BRB can be expressed as Eq. (15), which is used for global buckling design of SAA-BRB. For convenience of the design by engineers, \( \zeta / [\zeta] \) can be determined as a design coefficient. When the coefficient \( \zeta / [\zeta] \) value exceeds unity, i.e. \( \zeta > [\zeta] \), the satisfactory design of the SAA-BRB can be achieved by preventing its global buckling.

\[
\zeta \geq \frac{\omega W f_{yr}}{\omega W f_{yr} - P_y (v_0 + g)} = [\zeta]
\]  

(15)

5 Parametric study and design formula verification

Based on the proposed FE model, 24 FE hysteretic models listed in Table 5 were analyzed to conduct a parametric study and to verify the accuracy of the proposed formula (Eq. (15)) for global buckling design of SAA-BRB. The geometric dimensions covering commonly used dimensions in engineering practice are listed in Table 5, and the geometric parameters and material properties of the models are identical with the specimens in the experimental program. These 24 models were divided into 3 groups, and the core sectional area of models in each group were identical, and their corresponding values were 4356 mm\(^2\), 4796 mm\(^2\), and 6566 mm\(^2\), respectively. Besides, the loading protocol in the FE extensive analysis was determined according to the standard loading stage shown in Fig. 6, yet each loading step was applied for only one cycle.

Figure 19 shows the relationship between FE results and the coefficient \( \zeta / [\zeta] \). Figure 20 presents the hysteretic curves of representative FE models. The solid rectangles in Fig. 19 represent that the models maintained stable while the hollow rectangles
Table 5 Information of hysteretic models and FE results

| Group no | Hysteretic model no | Geometrical dimensions | Geometrical dimensions | Geometrical dimensions | $\omega$ | $\zeta$ | $\zeta' / \zeta'$ | FE results$^a$ |
|----------|---------------------|------------------------|------------------------|------------------------|--------|--------|----------------------|----------------|
| 1        | M-1                 | 1700 1400 110×22 100×6 | 4356                   | 0.548                  | 5.32   | 1.99   | 2.68 S               |
|          | M-2                 | 2000 1700 110×22 100×6 |                       | 0.580                  | 3.82   | 2.02   | 1.89 S               |
|          | M-3                 | 2300 2000 110×22 100×6 |                       | 0.606                  | 2.88   | 2.06   | 1.40 S               |
|          | M-4                 | 2600 2300 110×22 100×6 |                       | 0.627                  | 2.26   | 2.10   | 1.07 S               |
|          | M-5                 | 2900 2600 110×22 100×6 |                       | 0.645                  | 1.82   | 2.15   | 0.85 GB              |
|          | M-6                 | 3200 2900 110×22 100×6 |                       | 0.661                  | 1.50   | 2.20   | 0.68 GB              |
|          | M-7                 | 3500 3200 110×22 100×6 |                       | 0.675                  | 1.25   | 2.25   | 0.56 GB              |
|          | M-8                 | 3800 3500 110×22 100×6 |                       | 0.687                  | 1.07   | 2.30   | 0.46 GB              |
| 2        | M-9                 | 2300 2000 120×22 110×7 | 4796                   | 0.595                  | 3.86   | 1.94   | 1.99 S               |
|          | M-10                | 2600 2300 120×22 110×7 |                       | 0.617                  | 3.03   | 1.97   | 1.53 S               |
|          | M-11                | 2900 2600 120×22 110×7 |                       | 0.636                  | 2.44   | 2.01   | 1.22 S               |
|          | M-12                | 3200 2900 120×22 110×7 |                       | 0.652                  | 2.01   | 2.04   | 0.99 GB              |
|          | M-13                | 3500 3200 120×22 110×7 |                       | 0.666                  | 1.69   | 2.07   | 0.81 GB              |
|          | M-14                | 3800 3500 120×22 110×7 |                       | 0.679                  | 1.44   | 2.11   | 0.68 GB              |
|          | M-15                | 4100 3800 120×22 110×7 |                       | 0.690                  | 1.24   | 2.15   | 0.58 GB              |
|          | M-16                | 4400 4100 120×22 110×7 |                       | 0.700                  | 1.08   | 2.18   | 0.49 GB              |
| 3        | M-17                | 2300 2000 120×22 120×8 | 6556                   | 0.585                  | 4.01   | 1.96   | 2.04 S               |
|          | M-18                | 2600 2300 160×22 120×8 |                       | 0.607                  | 3.15   | 2.00   | 1.58 S               |
|          | M-19                | 2900 2600 160×22 120×8 |                       | 0.626                  | 2.54   | 2.03   | 1.25 S               |
|          | M-20                | 3200 2900 160×22 120×8 |                       | 0.643                  | 2.10   | 2.06   | 1.02 S               |
|          | M-21                | 3500 3200 160×22 120×8 |                       | 0.657                  | 1.76   | 2.10   | 0.84 GB              |
|          | M-22                | 3800 3500 160×22 120×8 |                       | 0.670                  | 1.50   | 2.14   | 0.70 GB              |
|          | M-23                | 4100 3800 160×22 120×8 |                       | 0.682                  | 1.29   | 2.18   | 0.59 GB              |
|          | M-24                | 4400 4100 160×22 120×8 |                       | 0.692                  | 1.13   | 2.22   | 0.51 GB              |

FE results$^a$ represents the failure mode of SAA-BRBs, in which “S” represents “stable”; “GB” represents “global buckling”. 
corresponded to models subjected to global buckling failure. When the $\zeta/\overline{\zeta}$ value is greater than unity, the global buckling failure of the FE model would be prevented and the corresponding hysteretic curves of the models maintained stable; when the $\zeta/\overline{\zeta}$ value is less than unity, the global buckling mode would occur in the FE model. Overall, a critical value (i.e., the value of red line) exists in Fig. 19, below which a stable bearing-capacity would transition to a global buckling mode. Taking model M-3 as an example, its $\zeta/\overline{\zeta}$ value is 1.40. It is seen from Fig. 20a that its hysteretic curve is full and symmetrical, indicating a stable bearing-capacity and satisfactory energy-dissipation capability during the whole loading process. Moreover, it is observed from Fig. 21 that the yielding had spread in the core while the restraining system remained elastic. This indicates that the full-sectional yielding load of the inner core could be achieved before reaching 2.00% axial strain. Furthermore, taking model M-13 as an example, its $\zeta/\overline{\zeta}$ value is 0.81. It can be seen from Fig. 22 that the model M-13 exhibited global buckling with a single-wave lateral deformation at the load step of 1.5% axial strain, thus severely pinched hysteretic curve was obtained as illustrated in Fig. 20e. Besides, stress concentrations were observed at the mid-span and both ends of the yield segment of the core, indicating that full cross-sectional yield load of the inner core could not be reached. Therefore, the accuracy of the formula (Eq. 15) of restraining ratio requirements for
Fig. 20  Hysteretic curves of FE models

(a) M-3 ($\zeta=2.88, [\zeta]=2.06$)  
(b) M-5 ($\zeta=1.82, [\zeta]=2.15$)  
(c) M-8 ($\zeta=1.07, [\zeta]=2.30$)  
(d) M-10 ($\zeta=2.44, [\zeta]=2.01$)  
(e) M-13 ($\zeta=1.69, [\zeta]=2.07$)  
(f) M-16 ($\zeta=1.08, [\zeta]=2.18$)  
(g) M-19 ($\zeta=2.54, [\zeta]=2.03$)  
(h) M-22 ($\zeta=2.54, [\zeta]=2.03$)  
(i) M-23 ($\zeta=1.29, [\zeta]=2.18$)

Fig. 21  Stress distribution of the SAA-BRB (model M-3)

(a) Whole member  
(b) Inner core
global buckling design of SAA-BRBs is validated, which can provide a valuable reference for practical designs.

6 Conclusions

In this study, the hysteretic responses of steel-angle-assembled buckling-restrained brace (SAA-BRB) were investigated experimentally and numerically. A design formula of restraining ratio requirements with high accuracy for predicting the global buckling of SAA-BRB was proposed and verified by parametric FE hysteretic analysis. The following conclusions can be drawn:

1. Through the experiments conducted on three specimens, the hysteretic curves and skeleton curves were obtained. It is found from the experimental results that all specimens maintained stable without global buckling, indicating that a proper-designed SAA-BRB can exhibit satisfactory hysteretic performance under cyclic loads. Based on the analysis of results from the experiments, it is found that the maximum equivalent viscous damping ratios of all specimens are greater than 0.50 and the compression strength adjustment factors are lower than 1.50 as specified in AISC. This shows that the SAA-BRB has favorable load-carrying performance and energy-dissipating capacity. In addition, the plane-section assumption is violated for SAA-BRB by analyzing the longitudinal strain distribution of the retraining system.

2. A refined FE model considering geometric nonlinearity and material nonlinearity was established. It is demonstrated that the results from FE analysis were consistent with those obtained from experiments, indicating the validity of the established model in predicting the hysteretic responses of SAA-BRB.

3. Based on the yielding criteria of outmost fiber for the restraining system section, the theoretical calculation formula of restraining ratio requirements $\zeta$ is derived. A parametric analysis involving 24 FE models was performed to investigate the accuracy of the proposed formula. It is verified that the proposed formula of restraining ratio requirement $\zeta$ is suitable for global buckling design of SAA-BRB in engineering practice. Moreover, a design recommendation for SAA-BRBs is that the lower limit of restraining ratio $\zeta$ can be approximately taken as 2.00 to prevent the global buckling of the SAA-BRB.
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Declaration

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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