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Buckling Restrained Braces: A review on Classifications, Design Strategy, and Applications

Osman Shallan, Hanaa E. Abd-El-Mottaleb, Abdelsattar El-Kahlawy*, Ebtsam Fathy

Structural Engineering Department, Zagazig University, Zagazig 44519, Egypt

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ABSTRACT

Buckling-restrained brace (BRB) is an evolution of conventional braces, where it is not only increases the compressive strength of the brace but also improves seismic energy dissipation. The fundamental difference between the BRB and common types of braces is that in the BRB, buckling is prevented by a restraining mechanism, which leads to a reduction in the cross-sectional area of the inner core. This results in plastic deformations of the inner core of the BRB without global buckling, which causes seismic energy dissipation. Due to the superiority of the BRB over other types of dispersing devices, many studies have been conducted to increase its efficiency and reduce costs. The scope of these studies was to develop the basic parts (core, restraining mechanism, and connections) of BRBs. In this paper, the results of some previous research over the past few decades are presented to illustrate the beginning, development, types, design strategy, and recent applications of BRBs. In addition, the advantages and disadvantages of the different types and methods used to model and analyze BRBs are also discussed.

1. Introduction

Earthquakes are among the most destructive natural disasters that can cause a lot of damage, especially in densely populated cities. Earthquakes occur when the Earth's tectonic plates move and slide, causing devastating waves that can cause severe property damage, injuries, and economic losses. Engineers need a deep understanding of how buildings react to earthquakes in order to develop efficient strategies and techniques that reduce loss of life and strengthen buildings' resistance to seismic forces. In the last century, researchers and engineers have presented numerous methods and techniques to mitigate the destructive effects of earthquakes and prevent structures from collapsing, thereby minimizing human and economic losses. Some essential earthquake-resistant methods include base isolation, energy-dissipating devices, passive control systems, and reinforced concrete or steel frames with ductile detailing. The purpose of these methods is to make buildings more resilient to earthquakes by increasing their ability to absorb and dissipate the energy produced by seismic forces. In addition to minimizing structural damage and deformation, and maintain structural integrity during and after an earthquake. Also, brace systems have been used to resist earthquakes for a long time. However, there were some drawbacks to using the brace system to resist earthquakes. One of the most significant of these disadvantages is that the earthquake-resistance

* Corresponding author. Tel.: +2-01069617796
E-mail address: aismail@zu.edu.eg.

strategy of this system depends on increasing the stiffness of the structure, which leads to an increase in the internal forces in the main structural elements (beams and columns). The brace system's efficiency in tension is excellent, but it has some issues in compression, which greatly affects its efficiency and results in an unsymmetrical hysteresis curve on both sides [1], [2], as shown in Fig. 1, and leaves permanent deformations in the structure.

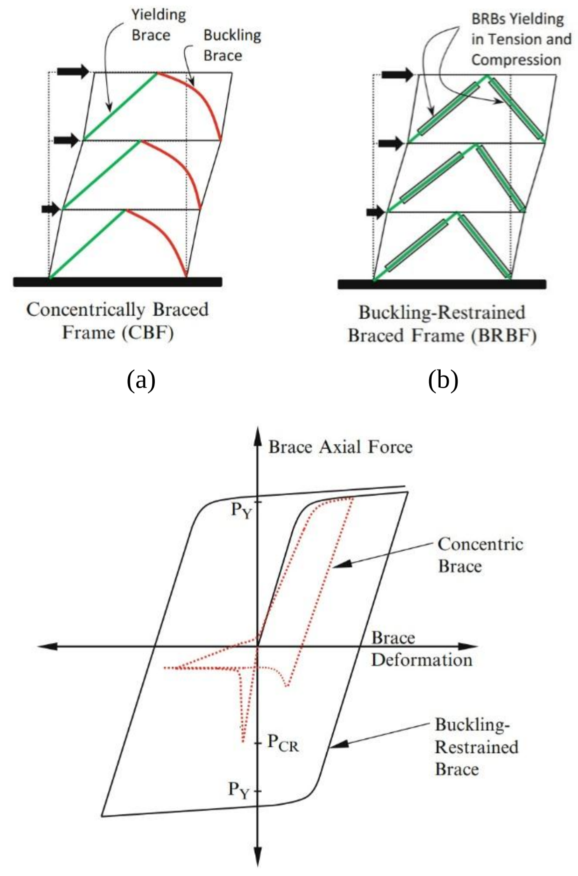


Fig.1. Comparison of the behavior of the concentric braced frame and the buckling restrained braced frame [2]

A "buckling-restrained brace" (BRB) is a new development that is a brace form in which global buckling is prevented by a sufficient restraining mechanism. (BRBs) are an earthquake-resistant structural element designed to dissipate energy during earthquakes [3]. In recent years, they have gained significant popularity due to their superior performance compared to conventional brace systems, as illustrated in Fig. 1b. As a result of preventing BRB from buckling, a symmetrical hysteretic curve is produced on the tension and compression sides, as shown in Fig. 1c, which explains the difference between BRB and the conventional brace. The earthquake-resistance strategy of the BRB system depends on dissipating the energy of the earthquake by allowing the inner core to yield in both tension and compression without causing global buckling [4]. As inner core buckling and overall element buckling are prevented, the BRB becomes more effective [5]. Due to the fact that the BRBs are weak in relation to the rest of the building elements, they are also often used as seismic structural fuses to keep buildings from collapsing during an earthquake [6]. BRB mainly consists of three parts: the non-yielding part, the restraining mechanism, and the core plate [7],[8] as shown in Fig. 2. The core plate (the yielding part) is designed using axial load design equations but no buckling-prevention procedures. The restraining mechanism doesn't carry any axial force, but its main job is to prevent the core plate from buckling. The non-yielding part consists of the connection and translation zone, which has a larger cross-sectional area than the inner core because it is designed to withstand the whole axial force acting on the BRB element without any buckling or yielding. This literature review discusses the history of BRBs, their fundamental components, and the key findings on the design, analysis, and applications of BRBs in building structures. It also presents the most significant findings from experimental, analytical, and theoretical studies conducted to enhance the BRB's efficiency.

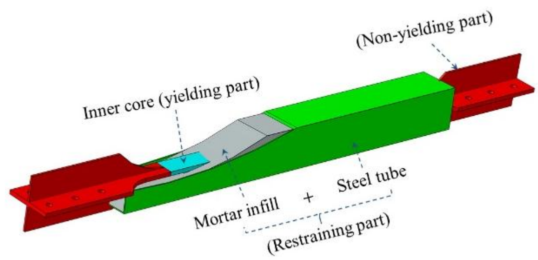


Fig.2. BRB's main parts [8]

2. Brief history of the BRBs

Steel-reinforced concrete structures were popular in the early twentieth century in Japan due to their superior seismic performance compared to reinforced concrete or steel structures. Therefore, Japanese researchers proposed a method of improving the seismic behaviour of the brace by inserting a deboning material between the concrete and the steel [9], and this can be considered the first practical form of the BRB concept. The year 1980 marked the initial development of BRB in Japan. A steel tube filled with concrete was used to confine the core element experimentally tested by Watanabe et al. (1988) and Watanabe et al. (1992) [10], [11]. They developed the BRB testing program, which validated the brace configuration's energy dissipation and ductility capabilities and clarified the fundamental requirements for the stiffness of the resisting mechanism. The results of the studies showed that the BRB provides excellent energy dissipation and stable hysteresis curves.

3. Development of BRBs

The Architectural Institute of Japan did not include BRB design recommendations in its structural guidelines until 1996, but the BRBs were used in two steel frame buildings in Japan in 1989, and by 1990, a total of 160 buildings had been constructed with BRB [12]. The first building in the USA constructed with BRB as an energy dissipation device was built by a team of American researchers and engineers in 1998; this was followed by an experimental study at the University of California in 2000 [13]. After the first design guidelines were included in AISC 341-05 [14], BRB began to be widely used across the United States. As part of a seismic retrofit project on a four-story building in Quebec City, Quebec, Canada, Tremblay et al. (1999) [15] conducted one of the earliest studies of BRBs in North America. China has many earthquake-prone regions, so the country has been very progressive in adopting energy-dissipation technology for use in structures. In 2001, the seismic design of buildings code GB50011-2001 [16] included the design criteria for the use of energy dissipation devices in structures. China published in 2013 a special code for seismically designed buildings with energy dissipation devices, including BRB, JGJ 297-2013 [17]. The fundamental principle of BRB is confining the core element so it can yield in compression as well as tension (Xie 2005) [18], so numerous studies have been conducted to maximize the BRB's effectiveness in compression by varying the restrained mechanism, core shape, core length, and connections.

4. BRBs classifications

The BRBs are classified into several types according to the restraining mechanism or according to the shape and properties of the yielding inner core, as illustrated in the next subsections.

4.1. BRB with different restraining mechanisms

Most researchers saw the development of the restrained part as an excellent area of search because it is very important to prevent the core element from buckling. Numerous studies have examined the change in the shape and material of the restrained part. The conventional mechanism is a steel tube field with concrete and unbounded material between the core and the concrete as shown in Fig. 3. However this is only suitable for short lengths because long lengths increase the weight of the brace and the total weight of the building, thereby increasing the earthquake force, so this conventional mechanism developed into all-steel BRBs as shown in Fig. 4. All-steel BRBs offer more benefits than conventional BRBs with mortar-filled steel tubes, including lightweight and the ability to control the spacing between elements. The second mechanism can be recycled if the restrained steel part collapses after an earthquake, while the first mechanism may collapse the concrete and destroy it. One of the most obvious problems with an all-steel BRB is the global buckling that may occur to the whole BRB.

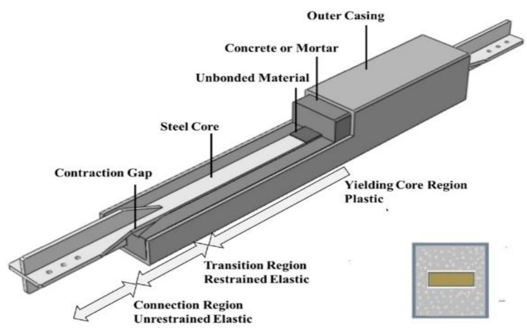


Fig.3. Typical Mortar-filled Steel Tube BRB [19]

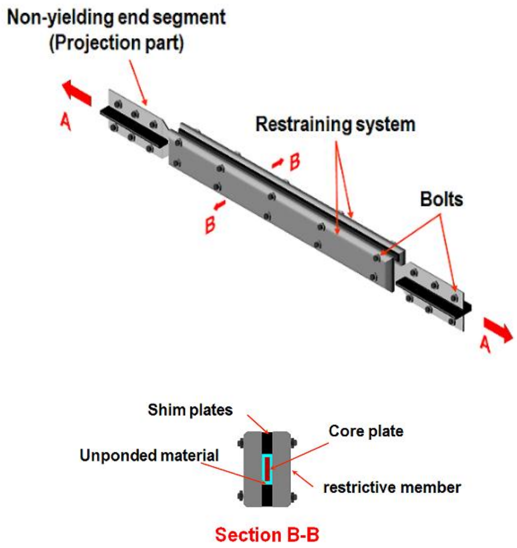


Fig.4. Typical all steel BRB [20]

4.1.1. Mortar-filled Steel Tube BRB

Comparing bounded and unbounded mortar-filled steel tube BRBs, Black et al. (2004) [21] conducted one of the most comprehensive studies. The experimental results validated the braces' inelastic capacity under severe earthquake demands and calibrated a hysteretic model that accurately predicted brace force-displacement behaviour. The study found that the unbonded brace is a reliable and useful alternative to traditional framing systems for earthquake resistance. Budaházy et al. (2015) [22] numerically analyzed concrete-filled BRBs, which were used in steel-braced frames as diagonal members to dissipate seismic energy. The study found that the smallest gap gave moderate contact stresses and buckling amplitude and reduced friction effects. However, the small air gap parameter prevents transverse contraction. Optimal air gap size and core cross-section shape can be determined based on the created numerical models. In an effort to enhance the restrained mechanism, Sun et al. (2019) [23] proposed a BRB with a steel tube filled with glass-fiber reinforced polymer (GFRP) instead of conventional concrete. Due to its high transverse strength, GFRP can successfully prevent local inner core buckling, according to the study. The cumulative plastic ductility values of GFRP-BRB specimens range from 297 to 310. Gao et al. (2020) [24] presented a new mortar-filled steel tube, BRB, which aimed to reduce the frictional force between the mortar fill and the inner core. The main concept of the proposed BRB is to install steel lining channels after putting un-bonding material around the inner core. Cyclic tests are performed on a conventional BRB and two of the proposed BRBs with steel lining channels. It is found that using the lining steel channels enhances the capacity of energy dissipation and the behavior of low-cycle fatigue.

4.1.2. All-Steel BRB

Due to its benefits, all-steel BRB has recently gained popularity, but there are some disadvantages to consider. The benefits of all-steel BRBs are their light weight, ease of maintenance, reduction of space surrounding the inner core, and simplified construction. The disadvantages are the expensive price and high sensitivity to corrosion. Numerous theoretical and experimental studies have compared the performance of all-steel BRBs to the conventional type, which uses concrete as a restraint member. To investigate the all-steel BRB's global buckling behavior. A parametric study of all-steel BRBs with varying gaps between the core and buckling restraint mechanism and initial imperfections is conducted by Hoveidae et al. (2012) [25] using finite element analysis. The results showed that the global buckling behavior of a brace may be significantly affected by the lateral stiffness of the restraint mechanism, regardless of the gap size, which affects the local buckling of the core element. All-steel web-restrained brace WRB is tested by Judd et al. (2016) [26] under cyclic loads to examine hysteretic performance under rotational loads and axial loads. A brace-and-column system was used to test WRB specimens for axial and rotational deformations. The test results demonstrated that the WRB was able to withstand a maximum compressive force similar to the typical types of BRB, although it was loaded with combined axial and rotational loads. As preventing the global buckling of a whole member when using a long-span BRB in a mega-frame high-rise building is challenging, Guo et al. (2017) conducted an experimental study [27]and Numerical study [28] that examined the cyclic behavior and design of a triple-truss-confine BRB (TTC-BRB). The TTC-BRB was developed by adding a rigid truss to the outsides of a standard double-tube BRB to increase the external restraint flexural stiffness, as shown in Fig.5. The experimental results demonstrate that TTC-BRB exhibited superior hysteretic responses and was capable of achieving stable hysteretic curves under cyclic loads. The failure mechanisms and design recommendations for the TTC-BRB specimens were also discussed based on the FE results, which provide the basics for further development o for the TTC-BRB.

Fig.5. Mega-TTC-BRB Proposed by Guo et al.(2017)[27], [28].

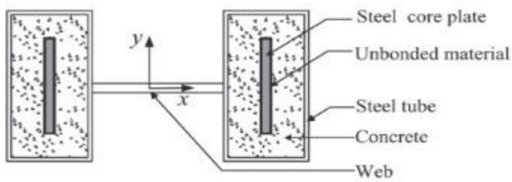
A new type of all-steel BRB was proposed by Gao et al. (2022) [29], which consisted of two steel tubes (inner and outer), one of which was round and the other square. Dissipating energy, mechanical performance, and axial strain distribution were evaluated by performing quasi-static cyclic load tests on two brace specimens. The findings demonstrate that the hysteresis curves of a double-steel-tube BRB are reliable and stable. There is no widespread instability, and energy dissipation performance is stable. Even after yielding, the core's capacity for plastic deformation remains stable.

4.2. BRB with different core

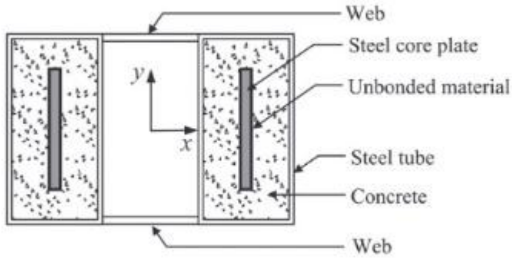
The fundamental idea behind the BRB is to increase stresses on the inner core until it reaches the plasticity stage in tension and compression without buckling in compression. Consequently, the hysteretic curve grows in both directions, resulting in an increase in the total energy below the curve, which reflects the increase in the amount of energy used by the element. Numerous studies have been done to examine the changes in the inner core that enhance the BRB's overall performance when subjected to cyclic loads. Some studies examined the effects of changing the inner core's shape, while others examined the effects of changing the inner core's length.

4.2.1. Core shape

The shape of the inner core has a significant impact on the local buckling that occurs to it, and thus on the overall buckling of the BRB. Furthermore, the shape of the inner core influences the amount of ductility that occurs under the influence of repeated loads and thus affects the behavior of the hysteretic curve. As a result, studying the shape of the inner core is an important factor in improving the overall performance of the BRB. The study by Guo et al. (2015) [30] presents a novel type of BRB that uses core-separated (CSBRB), as shown in Fig. 6. The CSBRBs consist of two cores and two chord members that are connected by one or more continuous web plates. The research shows that compared to conventional BRBs, the CSBRB has increased bending stiffness, making BRBs lightweight and easy to fabricate. As a result, CSBRBs can be installed in practical applications as a form of high-tonnage BRB.



(a) Section of single-web type



(b) Section of single-web type

Fig.6. CSBRB Proposed by Guo et al.(2015) [30]

Zhu et al. (2017) [31] proposed development in a core-separated BRB by connecting the two separated parts with the corrugated web (CWC-BRB). Experimental and analytical studies were carried out to evaluate CWC-BRB's performance. According to the findings, the restraining ratio has an effect on the global buckling of the CWC-BRB. The results indicate that CWC-BRBs have acceptable hysteretic performance and can be used as BRBs under large compression forces. Jia et al. (2017) [32] and (2018) [33] presented a new type of BRB in their research. The new type of BRB (FB-BRB) is a light-weighted all-steel BRB, and its core plate takes a shape like a fishbone as shown in Fig. 7. The FB-BRB consists of a core plate, two filling plates, un-bonding material, and two restraining plates. The main concept of the FB-BRB is to increase the deformation capacity by creating multiple necks at the core plate and reducing strain concentration at stoppers. Findings showed that the novel FB-BRB improved load and stiffness and generated stable hysteretic curves. Due to the interaction between the stoppers and the filling plates, secondary stiffness in the plastic stage of the FB-BRBs was comparatively higher than that of conventional BRBs. The tests produced excellent cumulative ductility and significant seismic performance.

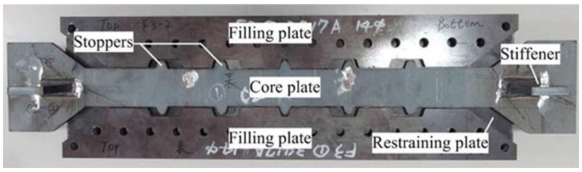


Fig.7. FB-BRB Proposed by Jia et al. (2017) [28]

Heidary et al. (2017) [34] introduced a new type of BRB called Tube-in-Tube BRB (TiTBRB), as shown in Fig. 8. Through a detailed finite element analysis, a parametric study was done on the important factors that affect how TiTBRBs behave and their failure modes when they are loaded under cyclic loading. Based on the results of finite element analyses, well-designed TiTBRBs can have stable cyclic behavior and good cumulative plastic ductility capacity, which lets them work well as hysteretic dampers.

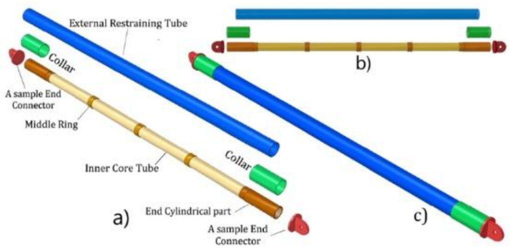


Fig.8: TiTBRB proposed by Heidary et al. (2017) [34]

4.2.2. Core length

The core length has a significant effect on the overall stiffness of the BRB, so experimental and analytical studies have been conducted to determine the significance of shortening the yielding part. These studies demonstrated the benefits of reducing the length of the yielding part, which improves structural efficiency by achieving high axial stiffness, less weight, a more flexible design, and simple restraint mechanisms. In addition, after severe earthquakes, it is not required to replace the whole brace. The BRB with a short yielding length provides adequate overstrength and facilitates plasticity distribution in the structure. Experimental studies on BRB steel core lengths were provided by Mirtaheri et al. (2011) [35] to examine how the core length impacts the BRB's overall performance, as shown in Fig.9. Experimental findings highlight the importance of taking the occurrence of low-cyclic fatigue and energy dissipation efficiency into account when designing BRBs with short lengths. Considering energy dissipation the only effective objective and ignoring other precautions may result in an unstable response, which is dangerous to the structure's stability. Researchers found that a BRB of only 1 m in length was able to effectively dissipate energy and also withstood loading until the final loading cycle.

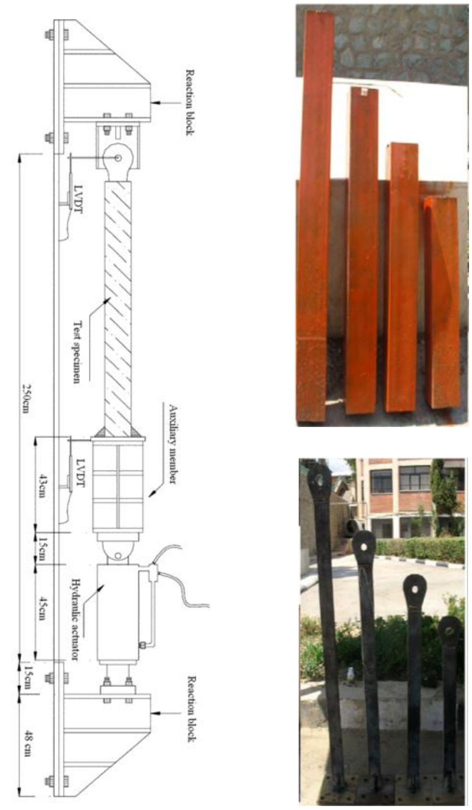


Fig.9: Experimental test conducted by Mirtaheri et al. (2011)[35] for four specimens with different core lengths .

Ali et al. (2014) [36] tested BRB with reduced core length in order to make it lighter and more replaceable and found that the BRBs with short core length exhibited stable hysteretic responses and withstood high axial strains of 4–5% without any global or local buckling. In order to assess hysteretic behavior, overall performance, adjustment factors, and energy dissipation of reduced-core-length BRB, Pandikkadavath et al. (2016) [37] conducted an experimental investigation on BRB with different lengths under cyclic loading. All BRB samples with a shorter core length showed magnificent energy dissipation and damping potential. Equivalent viscous damping was calculated at a core strain of 4.2% and found to have an average value of 43.5%. Pandikkadavath et al. (2016) [38] analysed the hysteretic response of BRBs of different lengths using ABAQUS software, as shown in Fig.10. According to FE results, changing the core length from 70% to 40% of work-point lengths can increase elastic stiffness by almost 22% and reduced the peak value of the inter-story drift and the residual drift response by 20% and 30%, respectively.

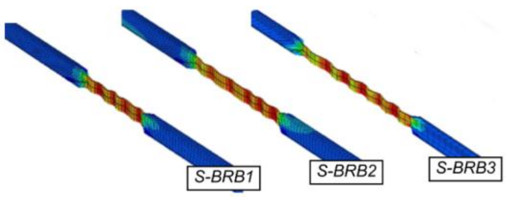


Fig. 10. Higher buckling modes of BRBs with different inner core lengths. Pandikkadavath et al. (2016)[38]

O. Shallan et al. (2023) [8] conducted a numerical study about the effect of the core length on the overall performance of the structure. Seven models of nine multi-story steel frames subjected to seven different historical earthquakes were utilized in the study. The seven models consisted of six BRBFs with different core lengths. According to FE results, changing the core length can decrease the inter-story drift ratio, as shown in Fig. 11. In addition, the total energy dissipation increases when the inner core length is decreased relative to the energy dissipated in the moment-resisting frame system, as shown in Fig. 12.

4.3. BRB with different types of connections

All components of the BRB are expected to affect the BRBF's overall behavior. BRB's connections are one of the most influential factors affecting the seismic performance of BRBF structures. Whereas, the transmission of seismic loads from the structure to the BRB is significantly influenced by the type of connections between the BRB and the surrounding structure. Moreover, the connections have a significant effect on the BRB's global buckling and, consequently, its resistance to loads that directly affect it. Therefore, numerous experimental and analytical studies have been conducted to examine the effect of varying BRB connections on the overall performance of BRBFs. An experimental investigation into the behavior of buckled gusset connections in a full-scale, three-story, three-bay concentric BRB frame was presented by Lin et al. (2005) [39], Fig. 13. The study also included a theoretical investigation and finite element analysis of gusset connections using the ABAQUS software. Results indicated that a stiffened gusset plate with stiffeners along the free edges effectively prevented out-of-plane buckling, increased rotational stiffness, and increased flexural demand on the BRBs.

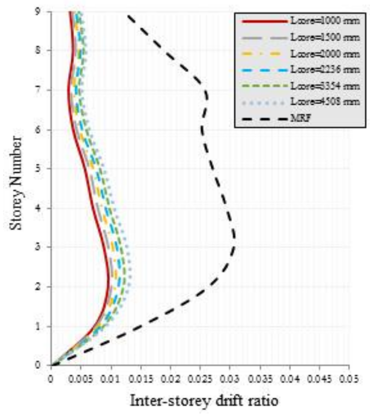


Fig.11. Comparison between Inter-story drift ratios for BRBs with different core lengths. Shallan et al. (2023) [8]

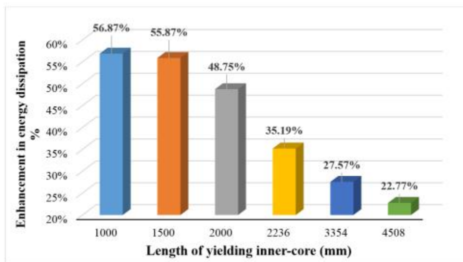


Fig.12. Comparison between dissipated energy in BRBs with different core lengths. Shallan et al. (2023) [8]

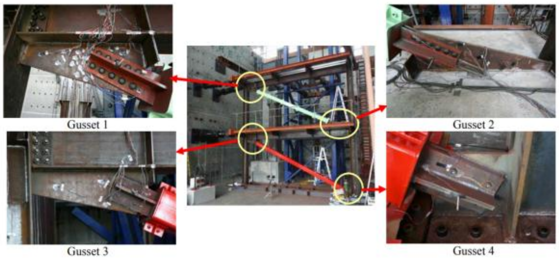


Fig.13. The four different gusset plates tasted by Lin et al. (2005) [39]

Wigle et al. (2010) [40] used nonlinear finite element models to examine the performance of variations in the configuration of the BRBF's brace-beam-column connections, the end condition of the beam, and the thickness of the gusset plate. The results showed that the beam end condition, either continuous or spliced, significantly impacted the story shear and drift behavior. There was 30% more story shear in the continuous beam cases compared to the spliced beam cases. The BRB end connection and gusset plate thicknesses had little effect on the behavior of story shear-drift. Where Gusset plates must be sufficiently thick to prevent large distributed stresses, but the stiffness should be proportioned between the connected members to prevent large strain concentrations at the interfaces. One of the important limit states of BRBs is global buckling due to the effects of the connections. Based on the bending transfer capacity of the restrainer ends, Takeuchi et al. (2016) [41] conducted tests with cyclic loading on BRB chevron configurations with various restrainer ends in upper and lower connections. Results showed that, under the same conditions, restrainer-end specimens exhibited stable hysteresis. This can be explained by the fact that the stiffness of the connection and the capacity of the restrainer to transfer moments have a significant effect on BRB stability. Nevertheless, the performance of BRBs is frequently hampered by the failure of corner gusset connections. Zhao et al. (2019) [42] utilized procedures for the design of the conventional gusset connection, followed by a finite element (FE) case study on the effect of frame action on the structural behavior of the gusset connections with two different strategies of gusset plates (sliding or dual). Results demonstrated that the sliding gusset connection reduced framing action and stress responses on the interfaces of the gusset plates and reduced shear force and plastic responses on the framing system.

4.4. Pre-tensioned cable stayed BRB

Guo et al. (2016) [43] proposed a new type of BRB, the pre-tensioned cable-stayed buckling-restrained brace (PCS-BRB), which is formed by adding an additional structural system of pre-tensioned cables and a number of cross-arms to the outside of a common BRB as shown in Figs. 14&15. This new system significantly increases the BRB's external stiffness. Guo et al. (2016) [43] introduced formulas for the elastic buckling load of pin-ended PCS-BRB. Finite element analyses were investigated to explore the effect on the axial compressive load-carrying capacity of the PCS-BRB through the elastic-plastic range. Theoretical and numerical analyses show that this PCS-BRB could buckle in two different ways: in a single-wave symmetric mode or in a double-wave anti-symmetric mode. In addition, the new restraint system used in PCS-BRB allowed the inner core to reach full cross-sectional yielding without PCS-BRB failure due to overall instability.

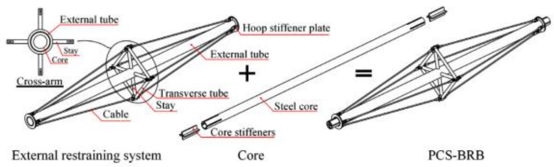


Fig.14. The pre-tensioned cable stayed BRB (PCS-BRB) Guo et al. (2016) [43]

Fig. 15. PCS-BRB in Tangshan, China. Guo et al. (2016) [43]

Pan et al. (2018) [44] analyzed and designed the PCS-BRB as a braced system using a simplified mid-span braced column model with translational and rotational springs as shown in Figure 16, to establish a more accurate design procedure for the PCS-BRB. In the study, a detailed design procedure and an elementary design example were presented. Based on the results of an elastic buckling analysis, it is found that the PCS- BRB with light bracing system can provide sufficient axial load capacity.

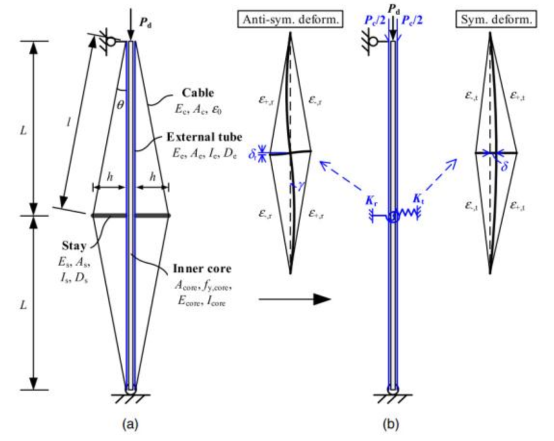


Fig. 16. (a) PCS-BRB (b) simplified model proposed by Pan et al. (2018) [44]

Zhou et al. 2020 [45] investigated the structural performance of double-arm pre-tensioned cable stayed BRBs (DPCS-BRBs) with fixed-ended stays and designed them using theoretical derivation and Finite Element Analysis (FEA) as shown in Fig. 17. The study began by investigating the elastic buckling behavior of DPCS-BRBs, focusing on the explicit formula prediction of the elastic buckling load under either symmetric or anti-symmetric buckling modes using the energy method. The obtained theoretical formulas were then validated using FEA. By using elasto-plastic FE models, the static load-carrying behavior and hysteretic performance of DPCS-BRBs were investigated. The results of the research would help engineers who use DPCS-BRBs with fixed-ended stays to design the structures.

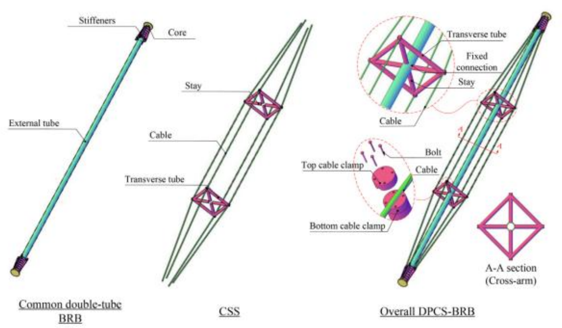


Fig. 17. Double-arm pre-tensioned cable stayed BRB proposed by Zhou et al. 2020 [45]

5. Design strategy of BRB

As a result of numerous experimental, analytical, and theoretical studies demonstrating the good performance of BRB, its design was required for inclusion in numerous international building codes. The design philosophy of BRBFs depends on the fact that the BRB is a yielding element, which is sized for a design seismic force level and is expected to undergo significant inelastic deformation during a design-level earthquake, while all other elements in the structure remain in the elastic stage. The ASCE 7-16 [46] specifies design criteria, redundancy requirements, seismic hazard level, irregularity conditions, and analysis methodology restrictions. AISC 341 [47] specifies the proportioning requirements to achieve the desired ductile behaviour, as well as the design of other elements and connections in the system BRBF.

5.1. Design steps of BRBFs

BRBs are designed to accommodate deformations corresponding to floor drift of at least the greater of the following two values: 2% of the floor height or a multiple of the design floor drift. The size of the BRBs is determined by ASCE 7-16 [46] load combinations with a response modification factor (R) equal to 8. The core must be capable of withstanding the entire axial force (compressive or tensile force C_r or T_r, respectively) acting on the BRB. The cross-sectional area of the inner core is calculated based on Equation 1.

$$C_r = T_r = \varphi AscFysc \tag{1}$$

where: A_{sc} is the inner core cross-sectional area, F_{ysc} is the core yield stress and ϕ equals 0.90 according to (LRFD)

After designing the inner core cross-sectional area, the adjusted strength of the brace is calculated to design the adjoining elements (beams and columns) and connections. This strength is calculated in compression and tension based on Equations 2 and 3, respectively.

$$C_{ysc} = \omega\beta A_{sc}R_yF_{ysc} \tag{2}$$

$$T_{ysc} = \omega A_{sc}R_yF_{ysc} \tag{3}$$

Where, β and ω are factors for adjustment of compression strength and strain hardening, respectively. These factors are determined based on qualification tests. R_y is the ratio between the expected yielding stress to the minimum yielding stress, whereas it equals 1 if the yield stress is determined depending on the results of the coupon test.

5.2. Modification factor of BRBFs

When designing BRBFs for seismic loads, it is common practice to account for the inelasticity and overstrength of the structure by reducing the elastic design seismic forces by a response modification factor (R-factor). Several seismic design codes have provided guidelines for estimating the BRBF R-factor. The Canadian national building code (NBCC-2010) [48] specifies BRBF ductility and over-strength factors of 4 and 1.2, respectively, which is equal to an R-factor of 4.8. The ASCE 7-16 [46] specification specifies the use of the R-factor in calculating design seismic forces as 7 and 8, respectively, for BRBF and MRF-BRBF dual systems. Several studies have been conducted to accurately determine the value of the R factor.

Multi-story steel frames' BRBF R-factors were evaluated by Mahmoudi et al. (2013) [49]. Multi-story frames with both single and double bracing bays and a variety of brace configurations had been subjected to nonlinear analysis. Height and number of bracing bays were found to have a greater impact on R-factor values. The R-factors obtained for various types of BRBFs with a single bracing bay ranged from 7 to 16 and from 8 to 22 for those with double bracing bays. Moni et al. (2016) [50] performed nonlinear static pushover and dynamic time history analyses on BRBFs with varying bracing configurations, span lengths, and story heights. Abou-Elfath et al. (2018) [51] conducted static pushover and earthquake time history analyses on low- to mid-rise BRBFs with an R-value of 4.5, which is equal to the R-factor of conventional bracing in accordance with the Egyptian code of loading ECP201-2012 [52]. Based on the results, it can be concluded that the BRBFs' R-factors are higher than the value specified by the Egyptian code. In the study, R-factors for the frames under consideration varied from 6.7 to 9.0 during earthquake analysis and from 5.0 to 13.5 during static pushover analysis. Since BRBs are so popular, the study concluded that the R-factor of BRBs should be included in the Egyptian code ECP201-2012 [52].

6. Finite element modeling of BRB

FE analysis programs were used in several studies to investigate the impact of changes in the BRB's parts on the BRB's overall performance. In addition to the BRB's overall ability to improve building performance. Several types of finite element models, such as detailed, simplified, and mixed models have been used to simulate and study the performance of BRBs. The detailed finite element model is a model in which the core, connections, outer steel tube, and concrete that fills the steel tube are modeled using an 8-node brick solid element. Surface-to-surface contact is defined for modeling the contact between all components as shown in Fig. 18. This model is used to investigate precisely the improvement of BRB performance by modifying its component parts. However, so far, it is difficult to use it to study and design large building models because it takes long time to do the analysis according to the capabilities of computers, which are widely used nowadays. Chou et al. 2010, Wu et al. 2014, and Piedrafita et al. 2015 [53]–[55] proposed new BRB and studied the performance of the proposed BRB by using a detailed finite element model. The detailed model was also used in Wang et al. 2018 and Avci-Karatas et al. 2019 [56], [57] to investigate changes in the performance of the BRB when various end connections were used.

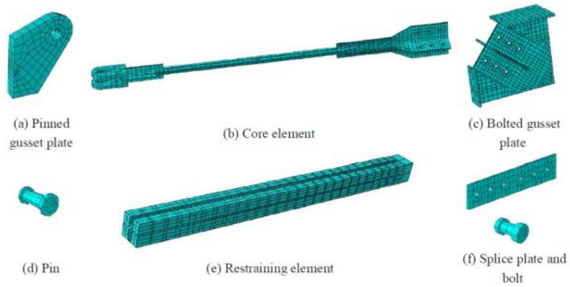


Fig. 18. The detailed finite element model. Wang et al. 2018 [56]

The simplified finite element model is a model in which all BRB components are replaced by a single truss element with the same axial stiffness as shown in Fig. 19. This model is able to examine the performance of large BRBFs. However, it does not have the ability to simulate the plastic deformation of the inner core plate, which results in better performance during earthquakes due to the greater dissipated energy. Furthermore, this model ignores the influence of frictional forces that occur between the inner core and the surrounding restraining systems, which greatly increase the compressive capacity. Shallan et al. (2023) [8] developed an enhanced simplified models, which simulate inner core and non-yielding parts separately as shown in the Fig. 20, to be able to study the effect of geometry of different parts of BRBs. Mahmoudi et al. 2013 and Moni et al. 2016 [49], [50] used the simplified model to determine the response modification factor of the BRB. Sabelli et al. 2003, Kiggins et al. 2006, and Sahoo et al. 2010 [58]–[60] used the simplified model to study the difference performance of using BRB in multistory buildings.

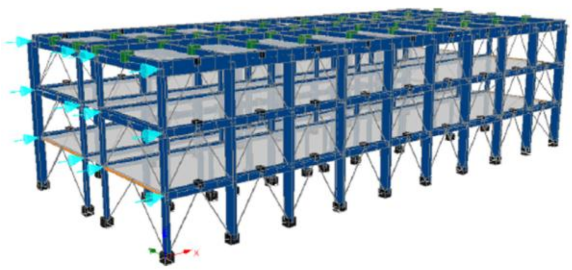


Fig. 19. The simplified finite element model. Almeida et al. (2017) [61]

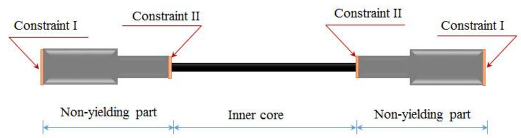


Fig. 20. The enhanced simplified model proposed by Shallan et al. (2023) [8]

Fathy (2023) [20] proposed a mixed FE model to simulate the actual performance of the BRBFs in large buildings without increasing the computational time of analysis. In this model, different material models and FE elements were used to simulate the nonlinearity of each part of BRBF as needed. Solid and contact elements used only to represent the inner core and restraining system of BRB to simulate the plastic deformation and friction forces accurately as shown in Fig. 21. The other parts such as non-yielding segments, columns and girder were represented using frame elements. Thus, the mixed model helps to combine the advantages of refined FE models and simplified ones.

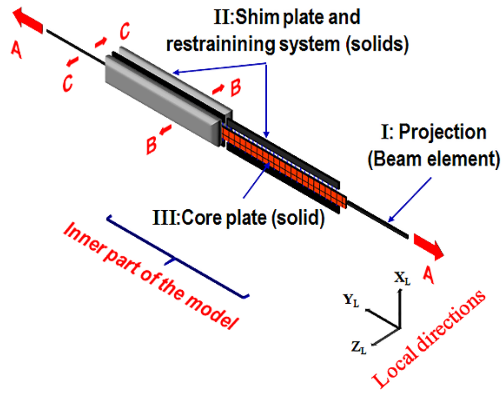


Fig. 21. The mixed finite element model proposed by Fathy (2023) [20]

7. Applications of BRB

Recent years have seen an increase in the use of the BRB as an energy dissipation device due to its low cost and ease of installation in structures. Designers have increased BRB usage in new high-rise structures. Additionally, it is preferable to use BRBs in structures that were designed in the past to be strengthened for earthquake resistance. Numerous studies have been conducted on BRB applications in new and existing buildings to resist seismic forces.

7.1. High rise buildings with BRBs

The resistance of lateral forces in high-rise buildings holds significant importance. The primary objective is to safeguard buildings from structural failure during seismic events and to ensure the safety of people. BRBs have become increasingly popular as energy-dissipating devices and fuses for today's high-rise buildings. The 181 Fremont Building is a tall structure situated in the central business district of San Francisco [62], Fig. 22. The seismic system used in the building is a dual system of a mega frame and Mega braces containing viscous dampers and BRBs. The BRBs were used to act as fuses to protect the building's primary and secondary elements during the maximum considered earthquake shaking.

Fig.22. Typical BRBs in Fremont Building [62]

The Wilshire Grand Centre is a seventy-three-story high-rise building located in Los Angeles [63], Fig. 23. The building's structural system consists of a concrete core wall with belt trusses and outriggers. In order to effectively mitigate drift caused by wind and seismic activity, the outrigger system was provided with 170 BRBs to provide the requisite stiffness and strength for the lateral system. During the installation of these BRBs, the consideration of strain compatibility with the shrinkage and creep of the concrete elements was taken into account. In Fukushima, Japan, the Koriyama Big-Eye Tower is a 24-story high-rise building [4], Fig. 24. Due to the great height of the building, the traditional methods of resisting the seismic forces to which Japan is constantly exposed were insufficient to protect it, so the designers resorted to using BRB to dissipate the seismic energy that is expected to influence the building during earthquakes.

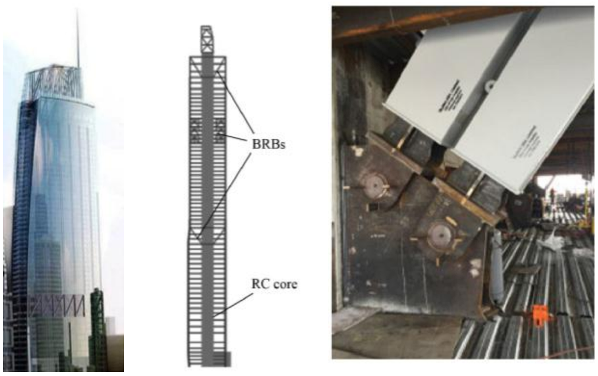


Fig.23. Outrigger system with BRBs in Wilshire Grand Centre building [50]

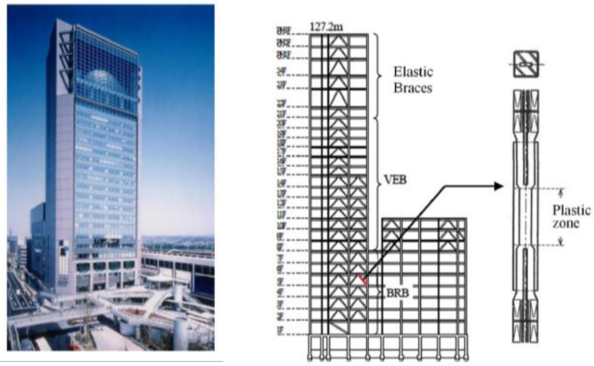


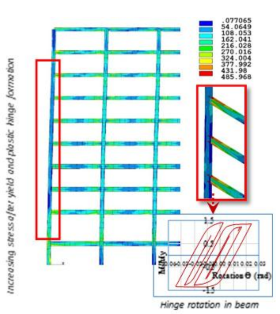
Fig.24. the Koriyama Big-Eye Tower [4]

7.2. Strengthening of existing buildings by BRBs

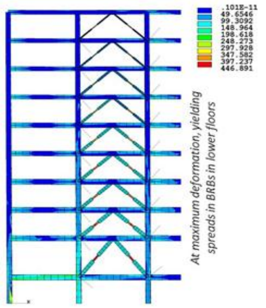
The evaluation of retrofitting existing steel frames with BRBs was the focus of an analytical study presented by Amiri et al. (2013) [64]. Before and after BRB retrofitting, the seismic response of typical steel frames was analyzed. The study's findings indicated that the installation of BRBs into pre-existing steel frames improved permanent drift distribution and allowed for better control of the maximum inter-story drift demand. Abdollahzadeh et al. (2014) [65] investigated the seismic performance of moment-resisting steel frames retrofitted with different bracing systems, including ordinary concentrically braced frames (OCBFs) and BRBFs. Study results demonstrated that maximum story drifts in BRBF heights were found to be more uniform than in OCBFs. Along its height, the retrofitted frame with BRBs responds more uniformly than OCBFs, without sudden changes in the deformation pattern or any deformation concentration in one story.

Almeida et al. (2017) [61] presented a nonlinear analytical investigation into the viability of retrofitting a typical pre-code reinforced concrete (RC) school building with BRBs. According to the results of the analyses, BRBs can be effectively utilized to improve the seismic performance of RC structures, particularly existing structures that do not comply with current codes. Damage is kept to acceptable levels when existing buildings are retrofitted with BRBs, which significantly increase their strength and energy dissipation capacity. Baca et al. (2021) [66] designed three traditional RC-framed structures with and without BRBs to mitigate earthquake-induced damage and vibrations in RC structures. Both structural systems are subject to a number of Mexico City's recorded ground motions. The study results indicated that BRB structures are more stable and reliable than conventional RC structures. BRBs can be used to improve the durability, seismic behavior, and overall structural reliability of RC structures that are exposed to severe earthquake ground motions. Fathy (2023) [20] made a rehabilitation study to retrofit a pre-Northridge, 9-story steel moment-resisting frame structure using the BRBs. A significant enhancement was found in responses such as inter-story drift ratios. In addition, all plastic deformations occurred in the inner cores of BRBs, not in the beams as in the original steel frame, as shown in Fig. 25.

As a result of the large spread of BRB, many factories were established to manufacture BRB with the required lengths according to the code used in the construction. BRB are manufactured in a variety of shapes by these factories, but the basic theory of the design remains the same. Fig. 26 shows how BRBs can vary in shape depending on the manufacturing facility.



(a)



(b)

Fig. 25. Stress distribution (a) before rehabilitation, and (b) after rehabilitation using BRBs [20]

(a) CoreBrace

(b) Nippon Steel

(c) Star Seismic

Fig.26. Different BRB shapes

8. Conclusion

BRBs have recently become one of the important systems that depend on them to resist earthquake loads because they give a balanced behavior under the influence of tensile and compressive forces as they overcome the problem of global buckling, unlike conventional concentric braces. It is also distinguished by its high ability to dissipate energy, as it acts as a seismic fuse during seismic action. The use of this type achieves sustainability because it saves the time and cost of repair after the earthquake, as it is easy to replace the inner cores that have plastic deformations with new ones, and the building regains its efficiency again. One of its disadvantages is the occurrence of residual displacement after the earthquake, but it is disposed of once these elements are replaced. To achieve the maximum efficiency of BRBs, they must be carefully designed so that the plastic deformations are confined to the inner yielding part and to avoid premature collapse in other parts, such as the projection parts and connections. As a result of the numerous experimental and numerical studies that were conducted for this system, the design method became available in many international standards. Therefore, this research focused on summarizing all the developments made by previous studies and identifying the most important factors that increase the efficiency of this system, in addition to explaining the design method and giving real applications for using this system in tall buildings and in strengthening buildings.

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