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Research Paper

Development of a novel high-performance multi-stage yielding buckling-restrained braces

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Abstract

Earthquake-resistant frame systems designed in accordance with current seismic provisions provide essential life safety during intensive ground motion. However, these systems often incur significant structural damage or residual drift due to energy dissipation in specific structural members, leading to challenging and costly repairs post-event. To address this issue, it is imperative to develop a structural system that effectively combines energy dissipation and self-centering properties to enhance the seismic performance of buildings. This paper presents a practical and cost-effective solution by modifying a conventional buckling-restrained brace (BRB) to achieve staged yielding in its core. The proposed multi-stage BRB (MSBRB) integrates isolated parallel cores with varying yield strengths: one core utilizes a low-yield-point (LYP) material with a lower yield strength, while the other employs high-strength steel (HSS) with a higher yield strength. This study rigorously examines the effects of different steel combinations on the re-centering behavior and energy dissipation of the MSBRB using ABAQUS finite element software. The results show that the dual-core MSBRB delivers stable hysteretic responses, appreciable energy dissipation, self-centering behavior, and large deformation capacity. Furthermore, the findings highlight that the strain hardening and yield point of the steels are critical factors in achieving a system with advanced seismic performance.

Keywords: Self-centering; Low yield-point steel; Seismic performance; Strain hardening.

1. Introduction

Earthquake-resistant building design is critical not only for safeguarding human life but also for mitigating significant economic consequences. Infrastructure c ollapse during seismic events can result in extensive financial losses, as evidenced by the 1994 Northridge earthquake in California and the 2011 Great East Japan e arthquake. Research by Moradi and Burton [1] highlights the profound economic impact of earthquakes, with recovery expenditures frequently amounting to billion s of dollars.

Investing in resilient infrastructure serves a dual purpose: it reduces immediate casualties and minimizes long-term economic disruptions. Modern seismic-resistant structures incorporate advanced engineering features, such as flexible steel frames, which are essential for mitigating damage and preserving structural integrity [2]. By prioritizing the durability and resilience of buildings, particularly in seismically active regions, communities can substantially lower reconstruction and recovery costs, thereby promoting sustained economic stability [3].

Buckling-restrained braces are a special type of concentric brace that exhibit ductility in both compression and tension under cyclic lateral loads. This results in a nearly symmetrical and stable hysteresis curve, leading to significant energy dissipation. Using this type of brace substantially reduces earthquake loads on the bra ced frame [4]. Researchers aim to improve these braces further, working toward ideal elastoplastic behavior. A key challenge with existing BRBs is their low post-y ield stiffness. This can lead to permanent structural deformations after significant earthquakes, potentially hindering the continued operation of the building.

One solution to address the problem of permanent displacement in frames with BRBs is to utilize a support bending frame system in conjunction with these bra cing frames as a dual system. This approach significantly reduces permanent displacements, as demonstrated in references [4, 5]. Researchers have also proposed ot her methods for mitigating permanent displacement in these frames. One method involves using BRBs with a short yielding core length (SCBRBs). This approach i mproves the elastic stiffness and post-elastic stiffness of the system, thereby reducing the risk of permanent floor displacements caused by design basis earthquakes (DBE) and maximum considered earthquakes (MCE) to some extent, as shown in reference [6]. Another potential solution is the use of shape memory alloys (SMA s) due to their numerous advantages, including hysteresis damping, high elastic strain range, high-cycle fatigue resistance, strain hardening at high strains, and stres s stability under seismic loads. However, despite these advantages, self-centering buckling-restrained braces also present certain limitations. The first drawback is th e high cost of manufacturing and machining SMAs, which must be considered when evaluating their feasibility for seismic applications. Additionally, the se lf-recovery mechanism only activates when the system enters the nonlinear region. Consequently, these self-centering BRB systems are unable to provide damping during low-intensity earthquakes [7, 8].

Another research study proposed a new approach to improve the performance of conventional BRBs across seismic risk levels, especially in low-risk earthquak es. This approach centers on hybrid buckling-restrained braces (HBRBs). HBRBs reduce permanent displacement, prevent dynamic instability, and offer cost savin gs. In HBRBs, one BRB core is constructed from low-yield LYP100 steel, and the other is constructed from high-strength HPS70W or HPS100W steel. This system combines low-yield point steel (LYP) with high-performance steel (HPS) in multi-core buckling-restrained braces (MC-BRBs). Frames equipped with hybrid buckl ing-restrained braces offer advantages. The LYP component yields before conventional steel, dissipating energy through yielding. This helps HBRBFs reduce struct ural response in low to moderate earthquakes. High-strength steel provides strength, and the strain-hardening properties of LYP counteract the low post-yield stiffne ss associated with conventional buckling-restrained braces. This, in turn, reduces the risk of dynamic instability during large earthquakes [9]. Sitler et al. [10] devel oped a multistage buckling-restrained brace (BRB) that incorporates two low-yield-point (LYP) cores with short yield lengths, along with one high-yield-point core that has a longer yield length. This design addresses the issue of low post-yield stiffness commonly found in traditional BRBs. Similarly, Hu et al. [11] introduced a two-stage yielding BRB design that achieves the desired structural behavior without the need for parallel dampers or multiple materials in the core plates. Additiona lly, Wu et al. [12] proposed a double-stage buckling-restrained brace (DSBRB) characterized by a progressive failure pattern. Testing revealed that the yielding disp lacement and force of the DSBRB were, on average, 7% smaller than those of conventional BRBs, resulting in a higher equivalent damping ratio for the DSBRB un der small deformations. Furthermore, Azizi et al. [13-16] conducted ongoing research into the cyclic behavior and seismic performance of high-performance BRBs (HBRBs). Their findings demonstrated the significant effectiveness of these braces in controlling seismic responses.

Although past research has identified some characteristics of the seismic behavior of multi-core BRBs, this work has been limited in scope. This research uses finite element analysis to investigate the cyclic behavior of double-core BRBs fabricated from different steels, evaluating their potential applications. All models are analyzed in ABAQUS finite element software using cyclic nonlinear static analysis under gradually increasing displacement loading.

2. Introduction of MS-BRB Configuration

As shown in Figure 1, the proposed multi-stage BRB (MSBRB) consists of isolated, parallel cores with differing yield displacements. A low-yield-point core (LYP) utilizes a material with a lower yield strain, while a high-yield-point core (HYP) employs a material with a higher yield strain. Within this system, the HYP core functions by providing the elastic restoring force. Conversely, the LYP core acts as a sacrificial member, dissipating plastic energy for the system through early yielding. The steel cores are connected in parallel to guarantee uniform deformation under cyclic loading. The unstressed restraint unit offers sufficient lateral buckling restraint for the MSBRB cores. This restraint necessitates sufficient stiffness and strength to prevent both the overall buckling of the MSBRB and the buckling deformation of the steel cores. A gap must be present between the steel core plates and the restraining components to obviate excessive contact force arising from the expansion and flexural deformation of the cores under pressure. This expansion is primarily induced by the Poisson effect. To minimize the friction force between the steel core components and the restraining component under compressive force, a non-stick material is interposed between them.

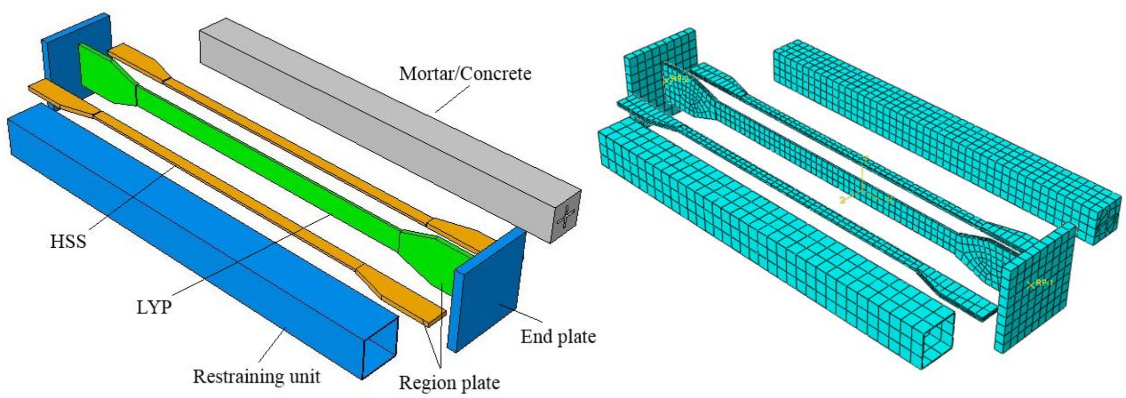

Fig. 1. Components of the proposed MSBRB

3. Finite Element Modeling

ABAQUS software was used to gain a comprehensive understanding of the design parameters that significantly influence the behavior of hybrid BRBs. Modeli ng and analyzing BRBs using a full, detailed model are challenging and time-consuming due to the large number of three-dimensional elements required. This appr oach becomes impractical because it is both expensive and time-consuming. Therefore, this study adopts a simpler approach based on the core-spring model (Figure 2), as previously validated for modeling hybrid BRBs [14, 15]. This model excludes the sheath, concrete, and non-adhesive material. However, other components, s uch as cores with rectangular cross-sections, end connections, and stiffeners, are modeled using the octahedral solid element with reduced integration (C3D8R). In t he modeling process, linear springs were incorporated outside the confined steel cores at each mesh grid node, oriented orthogonally within a plane perpendicular to the cores' longitudinal axis. The stiffness of these springs, a critical parameter influenced by mesh size and spring specifications, was determined through cyclic loa ding analysis of the core-spring model. The minimum effective spring stiffness was established by ensuring that the resulting hysteresis curve matched that of the ac tual model while precluding any potential buckling. This minimum effective stiffness represents the threshold value beyond which further increases in spring stiffne ss do not alter the analysis outcomes.

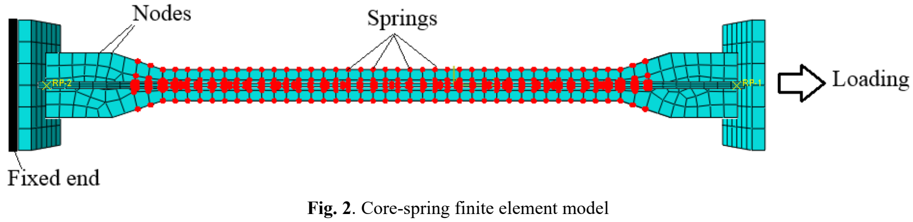

Fig. 2. Core-spring finite element model

In this study, kinematic hardening is used in the model to investigate the elastic-plastic behavior of cores within finite element (FE) software. Material characteristics were obtained from experimental results conducted by researchers and subsequently transferred to the software. To model the post-yielding behavior of MSBRB and BRB cores, which are anticipated to experience large inelastic deformations, real stress-strain values were entered into the software using experimental data and applied relationships. Table 1 presents the actual stress and strain values obtained for the different steel types used in this research.

Table 1. Mechanical properties of materials

Steel type	σ_y /Mpa	σ_u /Mpa	σ_y/σ_u	ε_u(%)	E /Gpa	Elongation $\in$(%)
S235	240	400	0/60	21.00	200	23
S460	485	585	0/83	14.00	200	19
S700	690	770	0/90	7.5	200	16
LYP100	100	250	0/40	27/00	200	47
LYP225	225	350	0/64	23/11	200	43

Where, E, σ_y, σ_u, ε, and ε_u represent the elastic modulus, yield stress, ultimate strength, elongation, and strain corresponding to σ_u, respectively. To describe the hysteresis behavior of the models, cyclic loading with incremental steps is applied following the AISC 341-16 protocol. This protocol consists of two cycles of $\pm\Delta_{by}$, two cycles of $\pm0.5\Delta_{bm}$, two cycles of $\pm\Delta_b$m, two cycles of $\pm1.5\Delta_{bm}$, and two cycles of $\pm2\Delta_{bm}$.

In modern structural engineering, both LYP and HSS play critical yet distinct roles in seismic design and construction. LYP steels, widely implemented in countries like China and Japan, serve as effective energy dissipators in systems such as shear walls and BRBs. Their low yield point, minimal yield ratio, superior ductility, and exceptional energy dissipation capacity enable them to yield before primary structural members, absorbing seismic energy and protecting the overall structural integrity [9]. Conversely, high-strength steels offer exceptional mechanical properties that make them ideal for tall buildings and long-span structures. Their high yield strength reduces member cross-sections and overall weight, enhancing architectural flexibility, usable space, and structural efficiency while minimizing welding and transportation requirements, delivering both economic and environmental benefits. Additionally, HSS provides excellent strength, fracture toughness, and weldability, solidifying its importance in advanced structural applications [10].

4. Validation

In this section, the numerical modeling methods are validated and matched with the experimental work presented by Tabatabai et al. [17]. The test conducted by the authors, in which a BRB with a core length of 1.2 meters was subjected to a progressively increasing static cyclic load, is numerically simulated. The BRB consisted of an 80 mm ×800 mm steel core enclosed by a steel sheath. The steel used in the experiment was ST37, with a nominal yield stress of 230 MPa. The modeling of the test specimen shown in Figure 3a was carried out based on the details provided by Tabatabai et al [17]. Figure 3b shows the finite element model of the BRB core. The core spring stiffness was determined experimentally by iteratively adjusting its value until the modeled BRB hysteresis curve closely matched the laboratory hysteresis curve. As shown in Figure 3c, the modeling results are in very good agreement with the experimental data. The minor discrepancies between the numerical results and laboratory values can be attributed to several factors, including inherent differences in the nonlinear material properties used in numerical modeling compared to real-world conditions. Additional contributing factors include simplifications in the modeling approach, the mesh size of the elements, and the selected boundary conditions.

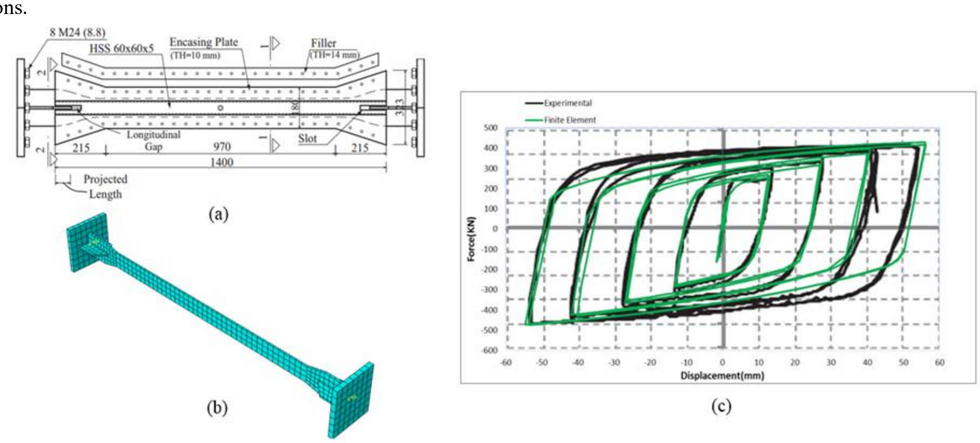

Fig. 3. Validation of numerical modeling.

5. Results

5.1. Cyclic Response

Figure 4 illustrates the force-displacement hysteresis curves of the models based on the loading protocol. Both models exhibit a stable hysteresis response, as shown. Comparing the curves reveals that increasing the yield strength in HSS cores leads to thinner hysteresis loops with higher load capacities. Consequently, the S460+LYP100 model exhibits a fatter hysteresis curve and lower load capacity compared to the S700+LYP100 model. Furthermore, the figure suggests a reduction in permanent deformations of the bracing member with increasing core strength in HSS steels. The permanent deformation, represented by the intersection of the loading-unloading loops with the displacement axis, signifies the amount of unrecoverable displacement. Therefore, the S700+LYP100 model demonstrates the highest restoring property. The superior recovery observed in HSS cores is attributed to the super-elastic behavior of these steels. It is important to note that while increasing the HSS resistance enhances the restoring capability, a certain degree of residual displacement persists in the system. Consequently, as indicated in the studies by [18,19], such BRBs are classified as partial self-centering BRBs.

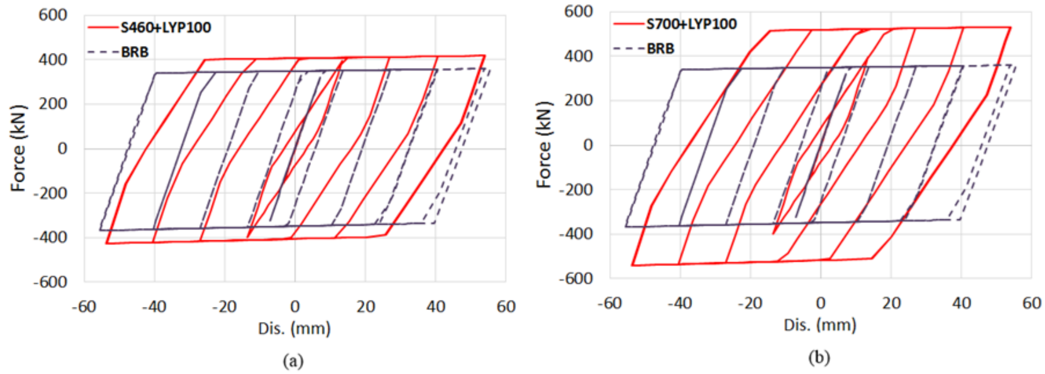

Fig. 4. Cyclic response of models

On the other hand, MSBRB models exhibit less permanent displacement compared to BRBs due to phase yielding at two points. This occurs because the LYP100 core, due to its low yield point, yields earlier than the corresponding cores (i.e., the A36 core in the BRB and the S460 and S700 cores) and governs the first yield point of the MSBRB model. At this stage, the S460 and S700 cores remain in the elastic region, providing restoring forces for the MSBRB model. As loading continues, once the yield strength limit of each high-strength steel (HSS) core is reached, these cores start yielding, leading to the second yield point observed in the cyclic response curve. During the plastic straining stage, both LYP steel and HSSs reach their yield limits, exhibiting tertiary stiffness equivalent to that of a BRB. At this stage, the LYP steel and HSSs collectively contribute to seismic energy dissipation. In a conventional BRB with bilinear kinematic hardening behavior, the unloading stiffness remains equal to the initial stiffness, resulting in relatively large residual displacements in the steel core component. In contrast, the multi-stage MSBRB demonstrates a distinct self-centering mechanism under reversal loading. Due to the early re-yielding of the LYP steel, the unloading path tends to converge toward the origin, thereby reducing residual displacements.

Figure 5 presents the von Mises stress and equivalent plastic strain (PEEQ) distributions for both MSBRB models. The results demonstrate a uniform stress distribution, with HSS cores exhibiting higher stress concentrations compared to other components. Notably, the end regions and connection points show minimal stress accumulation. In terms of plastic deformation, the LYP100 core displays greater cumulative plastic strains in both models, indicating more significant damage accumulation. Conversely, the A700 HSS core experiences reduced residual deformation, which is attributable to its larger elastic strain capacity.

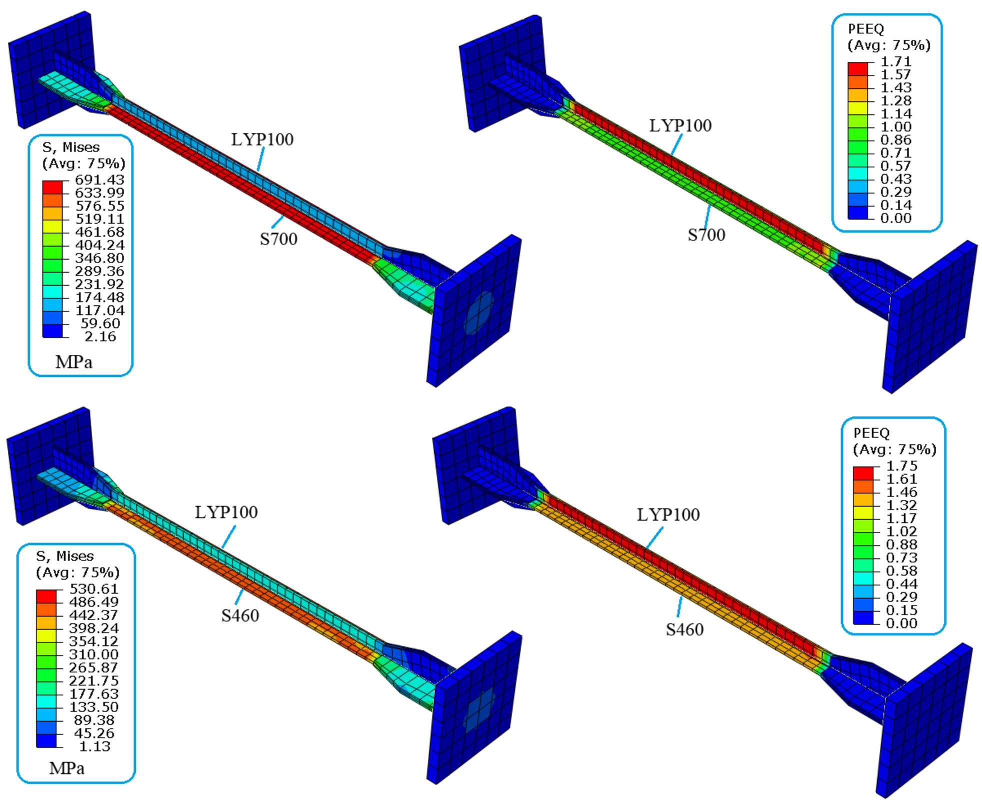

Fig. 5. Von Mises stress and equivalent plastic strain contour of the models

5.2. Cumulative Energy Dissipation

High energy dissipation capacity and proper ductility are important performance characteristics of non-buckling braces. Investigating cumulative plastic deformation is therefore necessary to evaluate the ductile behavior of models. Plastic deformation in each loading cycle is obtained by subtracting the displacement at the yield point from the maximum displacement. As lateral displacements increase, the energy consumed within each cycle also increases. The behavioral characteristics of the models are measured with an emphasis on hysteretic energy consumption. Cumulative energy consumption is an important measure of the seismic effectiveness of a system or structural member. Cumulative hysteretic energy values for different models were calculated numerically using FE software, with changes plotted in Figure 6. No energy consumption occurs during elastic cycles. Since MSBRB shows symmetrical behavior in compression and tension (as BRBs do), the amount of energy consumption in each loop of the cycle increases with lateral displacement. The maximum values of cumulative inelastic displacements for all models were obtained at a displacement of $2\Delta_{bm}$; the corresponding energy consumption values for each model are shown in Figure 6. A comparison of energy consumption reveals that the S700+LYP100 model consumes the most energy. The models all share the same LYP core, indicating that the HSS core influences the difference in energy consumption.

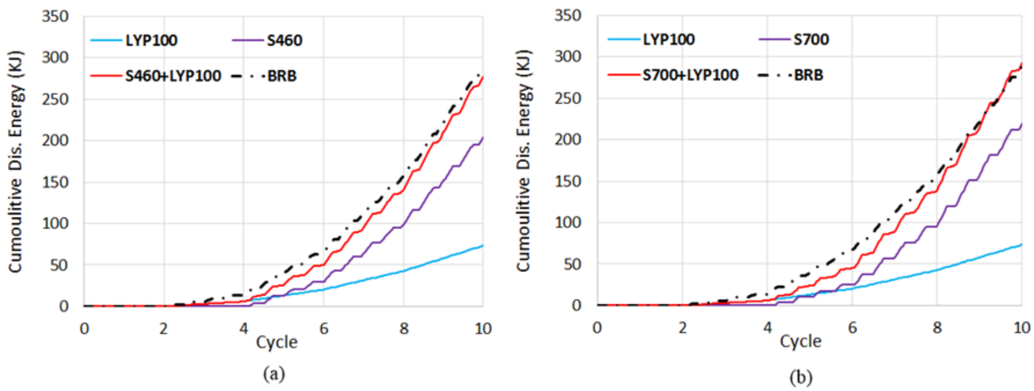

Fig. 6. Cumulative energy consumption of models

6. Conclusions

In this research, the concept of MSBRB braces was developed within the ABAQUS software environment. Based on the validation results and the assumptions used in the models regarding geometric features and materials, the following conclusions were drawn:

- MSBRB consists of two main components: a core with a low yield point (LYP) and a core made of high-strength steel (HSS). During minor and repeated earthquakes, the first core is expected to yield, dissipating energy within the brace. The second core remains elastic to maintain stiffness. Under severe earthquakes, both cores are designed to yield and dissipate the seismic energy.
- MSBRBs demonstrate a multi-stage yielding behavior along with notable post-yield stiffness. The early yielding of LYP100 enhances seismic energy dissipa tion capacity. Furthermore, the high strain-hardening properties of LYP100 impart substantial over-strength to MSBRBs, leading to superior re-centering cap ability compared to conventional BRBs.
- Increasing the yield strength of HSS cores leads to thinner hysteresis curves for the models, indicating a higher load capacity. Furthermore, it reduces permanent deformations in the bracing member. Consequently, S700+LYP100 models exhibit the least permanent deformation.
- Among models with LYP100 cores, S700 steel core models exhibited the highest cumulative energy consumption due to their superior yield strength. Notably, the LYP100 core absorbs initial energy, mitigating significant damage to the S700 core.
- The cost, installation, and construction methods of MSBRB are almost identical to those of BRB. However, due to its restorative properties, MSBRB can significantly increase the seismic resistance of structures, thereby reducing long-term structural costs. Additionally, compared to braces with shape memory alloy, MSBRB is easier to implement, has a faster design and manufacturing process, and is also more economical.

Statements and Declarations:

Author Contributions: Author 1: Investigation, writing – review & editing, writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis.; Author 2: Writing – review & editing, writing – original draft, Visualization, Supervision, Project administration. All authors discussed the results, reviewed, and approved the final version of the manuscript.

Conflict of Interest

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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