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Parametric Evaluation of Seismic Performance in Buckling-Restrained Braces Through Numerical Analysis

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Abstract – Buckling-restrained braces (BRBs) are crucial devices to mitigate the effect of earthquakes and provide stability for structures under seismic performance. These devices can assist in resisting damage from both tensile and compression states. This paper provides thorough parametric investigation into the effect of different design parameters namely friction coefficient and gap size on the seismic performance of structures. The main objective of this work is to clearly understand the influence of different parameters on the load carrying capacity, buckling resistance and energy dissipation potential on BRBs through an ABAQUS based FE model. The results indicate that meticulous selection for these parameters can significantly assist in enhancing the BRBs effectiveness and consequently to safer, more durable structures.

***Keywords*:** Buckling-restrained braces; Finite Element (FE) Modeling; Gap Sizes; Friction Coefficients

1. Introduction

In buildings and bridges, BRBs boost seismic performance by offering stable lateral support mechanisms throughout tension and stretching modes. In high-seismic regions, the construction of BRB systems have become increasingly popular. Particularly, as a result of their energy dissipation capability they may effectively serve as an alternative to conventional bracing method [1&2]. In general, a BRB is composed of a steel core contained in a steel case (usually an encasement equipped with section fillers where concrete is placed for hollow steel tube) to prevent the main core from buckling under compression load effect [3]. To improve the performance of BRB, a debonding gap is placed between the main steel core and concrete. This gap enables local buckling of the main core and causes uniform energy dissipation [3].

The behavior of BRBs is influenced by various aspects, including gap size between steel core and restrainer material as well as friction in the interface region among the main steel core and concrete surface. Consequently, the local buckling behavior and therefore the energy dissipation capability of bracing elements is significantly influenced by gap size [4]. However, design standards do not seem to provide a clear-cut answer here regarding what kind of gap size is optimal [5&6]. Likewise, the importance of steel-core/concrete friction in load transfer under compression loading is considered critical for both BRB stability and force redistribution within the BRB [7].

In this paper, a detailed parametric study is conducted to investigate the effects of gap size and friction on the BRB's behavior under cyclic loading. Friction coefficients between 0.1-0.7 and gap sizes between 1.4 mm–15mm are considered in the analysis. This paper gives insights to optimize BRB design for seismic applications by investigating the impact of these parameters on energy dissipation and maximum force capacity. A detailed description of force-displacement behavior and energy dissipation characteristics are obtained from ABAQUS simulations. The present work will provide insights into the relationship between gap size, friction and BRB performance to expand understanding of how these behave under seismic loading conditions so as to guide practical recommendations for effectively enhancing stability while retaining energy absorption in a safe state.

2. Experimental Test from Literature

In this paper, the seismic performance of BRBs is investigated experimentally by considering a single specimen with a 2.8 mm gap between steel core and concrete restraining member as shown in Figure 1. The performance of this BRB is evaluated after being tested experimentally under the standard loading protocol recommended by the AISC. The steel core has a rectangular cross section with 10 mm thickness, and it is enclosed in the square hollow profile of 100×3 mm to form a BRB specimen that has been originally tested by [8]. A depending gap equal to 2.8 mm is placed to separate the core from the concrete filling to provide local buckling and energy dissipation capabilities. A finite element model (FEM) is prepared to predict the behavior of this system as well as identifying the key parameters affecting the BRB's performance. Numerical model is validated against experimental data from [8], leading to proper simulation for the force-displacement behavior and energy dissipation capacity under cyclic loads. Figure 2 shows the BRB model with labels of the critical dimensions and configuration that was tested.

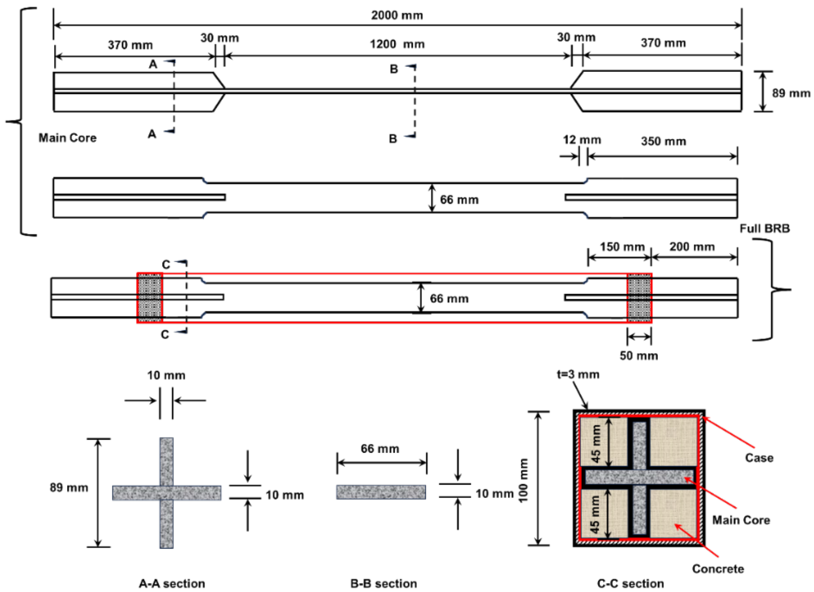

Figure 1: Dimensions and configuration of BRB specimen with 2.8 mm gap (adapted from Slama and Düğenci, 2022).

3. Finite Element (FE) Modeling

This paper utilized a 3-D nonlinear FEM established in ABAQUS to evaluate the seismic behavior of BRBs when subjected to the AISC cyclic loading regulation. The developed FEM model tries to replicate BRBs with a 2.8 mm gap between steel core and concrete. To perform this, the main parts of a BRB system were—core, infill concrete and steel case—attempted to be included in the FEM model. Figure 2(a) shows this clearly, with the core parts and steel casing that introduces to restrain the core. This model effectively captures the interaction between these parts, especially when subjected to axial AISC cyclic loading. In Figure 2(b), the displacement and boundary conditions applied to the involved model are demonstrated. A fixed boundary condition was imposed at one end of the BRB, while oscillating displacement was enforced on the opposing end to mimic seismic situations. These boundary constraints are pivotal for precisely replicating real behavior in a regulated environment.

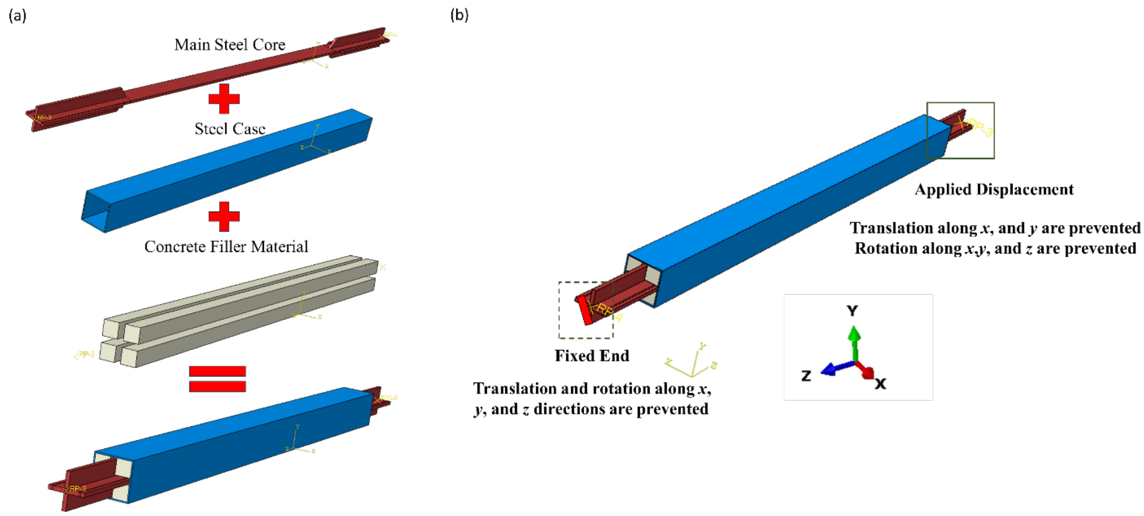

Figure 2: (a) The developed 3-D finite element (FE) model showing the main components of the BRB system. (b) Applied boundary conditions and displacement configuration for cyclic loading.

The AISC loading protocol, as shown in Figure 3, was applied during the cyclic tests, ensuring that the BRBs were subjected to industry-standard displacement sequences. The AISC loading protocol outlines the amplitudes and cycles applied to the specimen, and the FE model followed this same protocol to ensure consistency with the experimental procedures. The deformed shape and the von Mises stress distribution at the ultimate compression load cycle for specimen with gap size equal to mm is presented in Figure 4. Figure 5 shows the validation of the FE model, presenting the hysteresis curves obtained from both the numerical model and experimental data. The curves demonstrate that the FE model accurately captures the energy dissipation and ultimate capacity of the BRB. The close agreement between the FEM and experimental hysteresis curves further confirms the model's effectiveness in simulating cyclic behavior. In conclusion, the developed FE model provides a comprehensive understanding of BRB behavior under seismic loading. The integration of core, filler, and steel case elements, along with accurate boundary conditions and the AISC loading protocol, allows for precise simulation and validation against experimental data. The model's ability to predict forces and energy dissipation with minimal error ensures its reliability for future parametric studies and practical applications.

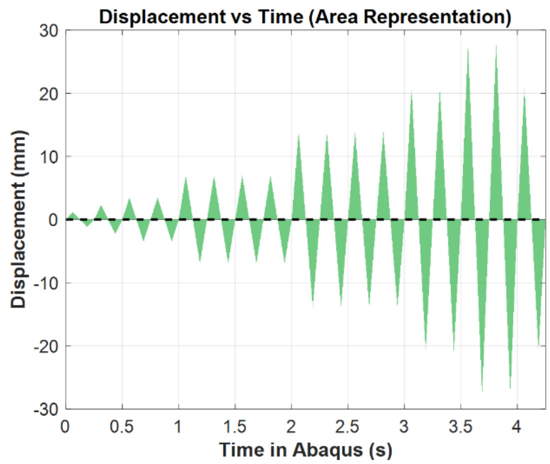

Figure 3: AISC cyclic loading protocol used in the simulation.

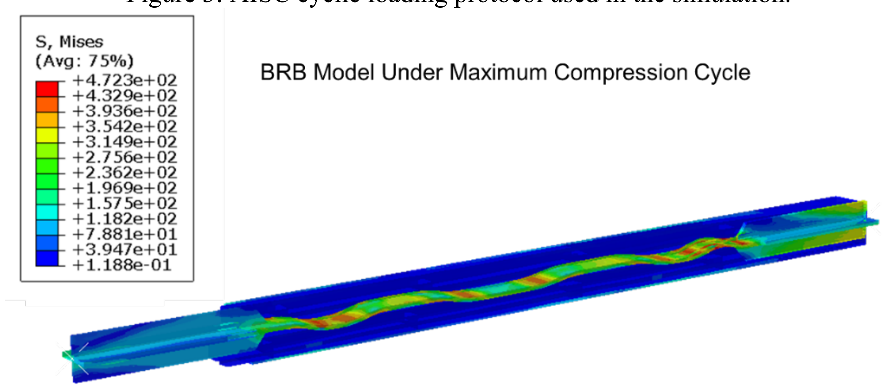

Figure 4: Stress within the BRB in MPa and main core at the maximum compression cycle.

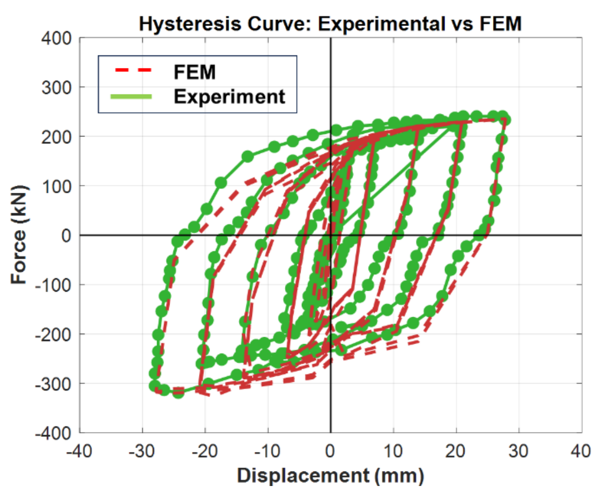

Figure 5: Comparison of hysteresis curves obtained from the finite element (FE) model and experimental data.

4. Results and Discussion

- **Impact of Debonding Gap Sizes**

This study demonstrates the significant impacts of both gap size and friction coefficient on seismic performance of BRBs. Force-displacement curves under maximum cycle in tension and compression according to the AISC loading protocol are provided in Figure 6 for different gap sizes from 1.4 mm up to 15 mm. It was found that smaller gap sizes improve the force capacities. For instance, BRB with gap size equal to 1.4 mm results in increasing tension forces by about %5 compared to baseline (2.8 mm) configurations. This is due to better confinement of the steel core, which prevents buckling and enhances resistance. In contrast, larger gaps, such as 15 mm, lead to a 19% decrease in force capacity, as the core-concrete interaction weakens, allowing greater core deformation and reducing the BRB's force resistance. These findings suggest that optimizing the gap size is essential to maximize the structural efficiency of BRBs under cyclic loading, with 2.8 mm providing a balanced performance between ductility and resistance. In terms of energy dissipation, **Figure 7** shows that smaller gap sizes lead to higher energy absorption, with the maximum cumulative dissipated energy of 151 kN.m occurring at a gap size of 1.4 mm. As the gap size increases, the energy dissipation steadily declines, reaching 66 kN.m at 15 mm. This reduction is attributed to the decreasing interaction between the steel core and the surrounding material, allowing more significant deformations. Optimizing the gap size to around 1.4 mm ensures the most effective energy dissipation, making it critical in seismic design. It is worth noting that a smaller gap size than this limit (i.e., half of the radius of gyration e.g., 1 mm) would escalate buckling at the gusset plates, thus causing local deformations to appear at the ends of the restraining members [9].

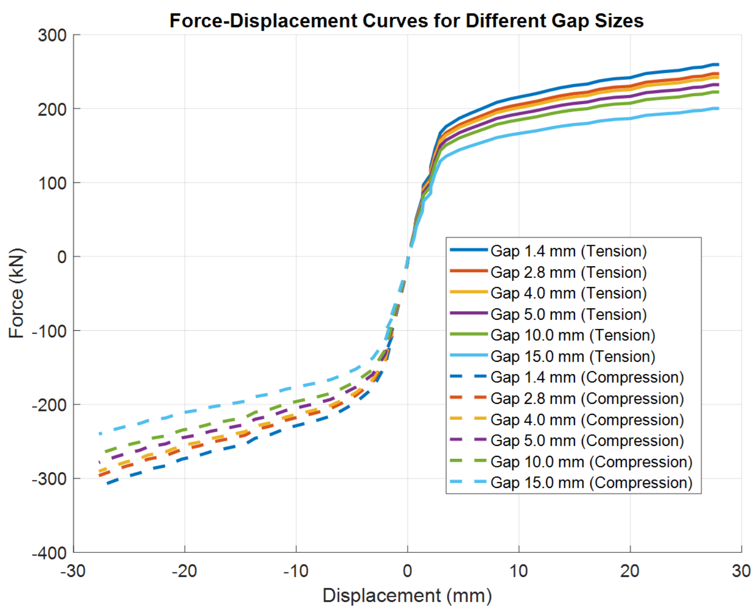

Figure 6: Force-displacement curves for different gap sizes under tension and compression.

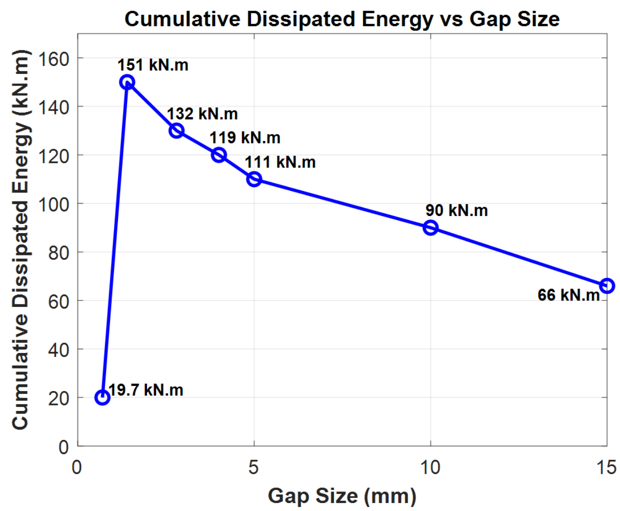

Figure 7: Cumulative dissipated energy as a function of gap size.

- **Effect of Friction Coefficients**

The effect of friction between the steel core and concrete is shown in **Figures 8(a)** and **8(b)**. As the friction coefficient increases from 0.1 to 0.7, the maximum axial force rises slightly, from 290 kN to 330 kN. However, the increase plateaus beyond a friction coefficient of 0.5, indicating that higher friction levels offer diminishing returns in terms of force resistance. Similarly, energy dissipation improves as the friction coefficient increases, reaching 159 kN.m at 0.7, but with less pronounced gains after 0.5. Thus, the optimal range for friction lies between 0.25 and 0.5, where both force resistance and energy dissipation are maximized without excessive friction leading to material stress concentrations. To sum up, gap size and friction coefficient have a notable impact on the seismic response of BRBs. Optimal force resistance and energy dissipation are achieved by utilizing small gap sizes and moderate friction levels.

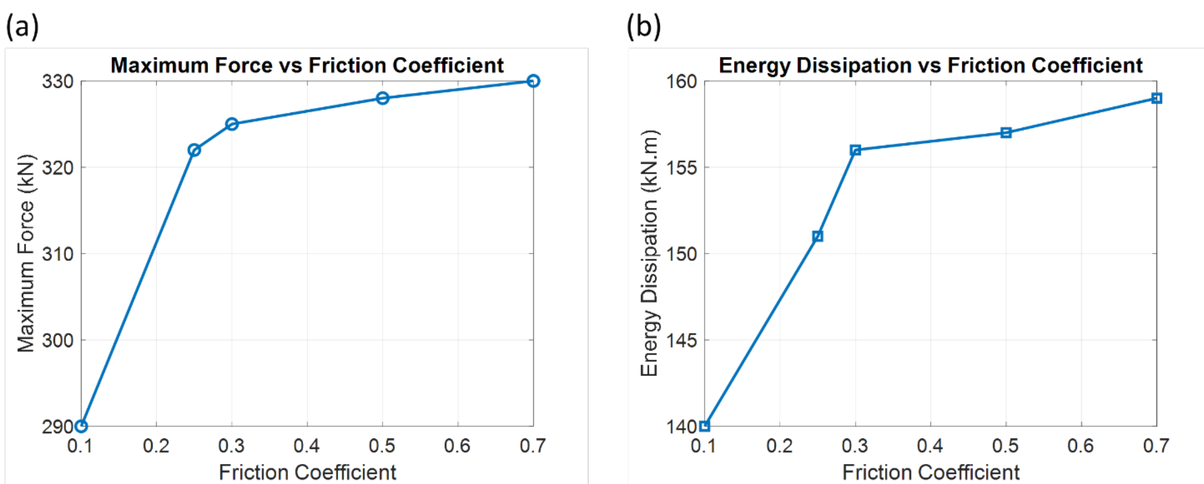

Figure 8: (a) Maximum axial force as a function of the friction coefficient between the steel core and concrete filler. (b) Energy dissipation as a function of the friction coefficient.

5. Conclusions

This paper investigated the seismic performance of BRBs under various gap sizes and friction coefficients. A FE model in ABAQUS was constructed, validated, and then utilized to perform parametric analysis. Notably, the results showed that smaller gaps — particularly at 1.4 mm — significantly improve force resistance and energy dissipation over larger gap configurations which delivered underling performance. In comparison, it was found that a friction coefficient between 0.25

and 0.5 improved the energy absorbing property as well as optimal force resistance; however, beyond 0.5 coefficient of frictions it had little effect. Therefore, it is of significance to optimize both gap size and friction in designing BRB for overall improved stability, as well energy dissipation under seismic loading. Thorough consideration of these parameters could contribute to securer and more sustainable structures against earthquakes.

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