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SEISMIC PERFORMANCE OF STEEL FRAMES WITH ALUMINIUM BUCKLING RESTRAINED BRACES

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Abstract

To increase the seismic capacity of buildings, energy-dissipating devices are installed primarily to dissipate the seismic energy, thereby limiting the damages to main structural components. These devices undergo inelastic deformations, acting as a fuse, sacrificing themselves and requiring replacement after a seismic event. In this study, Aluminium buckling-restrained braces (BRBs) have been used to enhance the seismic strength of buildings. Aluminum alloys are softer than steel and can provide more ductility. Besides, these devices also transfer less amount of force to the connections, thereby resulting in smaller member sizes. Furthermore, Aluminium BRBs exhibit an almost symmetrical hysteresis loop. The analysis has been performed for different configurations of the Aluminium BRB and their performances are compared. The stress-strain behavior of Aluminium BRB is modeled using experimental data. The analysis is carried out in OpenSees, where the 3-story SAC Building is subjected to different earthquake time histories. The buildings are designed according to AISC guidelines. The analysis of the structure with and without the Aluminium BRB indicates that the seismic demand on the primary structural members is reduced with the incorporation of the Aluminium BRB. This offers the potential for utilizing Aluminium BRB in the design of new structures and the retrofitting of existing ones.

Keywords: Aluminium, Buckling-restrained brace, Earthquake-resistant design, Energy dissipation, Seismic analysis, Steel buildings.

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1 INTRODUCTION

The design of buildings to withstand earthquake loads presents several challenges due to the random and dynamic nature of these loads. Moreover, rapid urbanization has led to the construction of high-rise buildings to accommodate the surge in the population in metropolitan cities. These structures need to be designed to withstand earthquakes to prevent loss of life and damage to infrastructure. However, it is neither practical nor economical to design structures to elastically withstand earthquake loads [1,2]. Thus, the philosophy behind earthquake design has evolved over the years, influenced by new construction materials and advancements in our understanding of how structures behave during seismic events. Besides, many governing bodies have implemented stricter regulations to ensure that buildings do not collapse during an earthquake. However, older buildings constructed without adherence to recent building codes remain vulnerable and may suffer significant damage or even collapse in the event of an earthquake.

Therefore, the introduction of new technologies for both new construction and the retrofitting of older buildings is necessary. Several techniques have been developed to control the response of a structure to earthquake loads, which can be broadly classified into active, passive, semi-active, and hybrid control systems [3-5]. Among these, passive systems are extensively used due to their simplicity and ease of application. One widely used passive energy dissipation system is metallic yielding dampers, which utilize hysteretic behavior to provide seismic damping to a structure[5]. Buckling-restrained braces (BRBs) are a type of metallic yielding damper in which the mechanisms for buckling resistance and axial load resistance are separated [2]. BRBs Exhibit stable and symmetric hysteresis behavior [6]. Frames fitted with BRBs have a higher response reduction factor, *R* resulting in a reduced base shear for design.

BRBs consist of a core that resists axial loads and undergoes inelastic deformation, while the restraining member prevents the core from buckling [7]. This design allows the core to fail by fracture instead of buckling, as observed in conventional braces. These devices act like fuses, which sacrifice themselves during an earthquake to protect the structure, and they need to be replaced after the earthquake event. Conventionally, BRBs are made with a steel core and steel casing, and they have been patented and commercially used in various countries. In these systems, concrete is often used as filler material inside the steel casing. BRBs with a steel core and angular steel restrainers have also been proposed [7-8]. Moreover, there is a continuous quest for better technologies in terms of material and shape to enhance the performance of BRB. This study focuses on the performance of aluminum BRBs, which are made with an aluminum core and aluminum restrainers, in resisting seismic loads.

2 ALUMINIUM BRB

BRBs utilize their inelastic deformation of the material to dissipate seismic energy. These devices are specifically designed to yield before the main structure, undergoing hysteresis to provide damping to the primary frame, thereby concentrating damage in these devices. Although mild steel is commonly utilized in BRB cores, researchers are exploring materials with a lower yield point and similar ultimate strength and ductility to mild steel. This resulted in the introduction of Low-Yield Point Steel in BRBs and Shear Links [9-10].

In this context, aluminum is one of the suitable materials for BRBs due to the following characteristics: (i) Low yield point, yet comparable ultimate strength to steel, (ii) Sections can be made bulkier, leading to delayed onset of buckling, (iii) Higher ductility, (iv) Lighter in weight compared to mild steel, (v) Lower stiffness, resulting in reduced demand on the main structure, and (vi) Cheaper and readily available in the market than the Low-Yield Point Steels.

The above properties make aluminum a potential choice for use in BRB. Moreover, Aluminium has been successfully used as a construction material for decades [11–13]. Aluminium has also been used as dampers like shear links[14–16] and shear panels [17–21]. Several studies have been conducted to assess the performance of BRBs made with aluminum cores [22–31]. Avci-Karatas and Celik [32] performed experiments on aluminum core BRB with an aluminum case filled with concrete. Usami et al. [33] conducted experiments on both welded (ribs and stopper) and bolt-assembled aluminum core BRBs with aluminum restraining members.

In this study, the performance of the Aluminium BRB in resisting the seismic loads in a 3-story steel building has been analyzed. The Aluminium BRB used in this study has been taken from the literature. Wang et al. [31] conducted component tests on extruded aluminum BRBs. The BRB consists of a core made of extruded aluminum with ribs and a stopper. The extrusion was performed to avoid premature failure caused by residual stress from welding the ribs and stopper to the core. Avoiding welding also enhanced the fatigue life of the brace. The core of the BRB is shown in Figure 1.

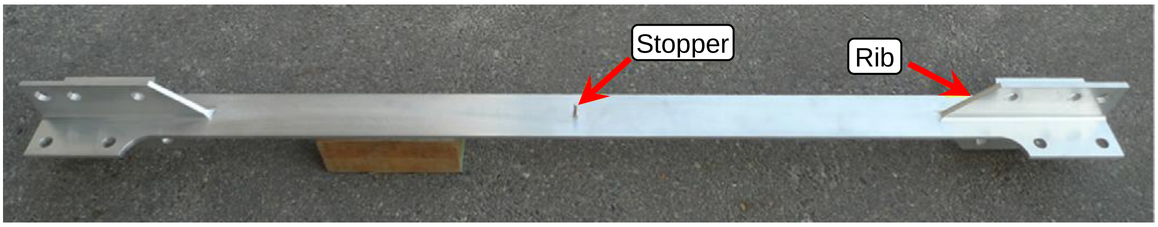

Figure 1. Aluminium Core of the Extruded BRB

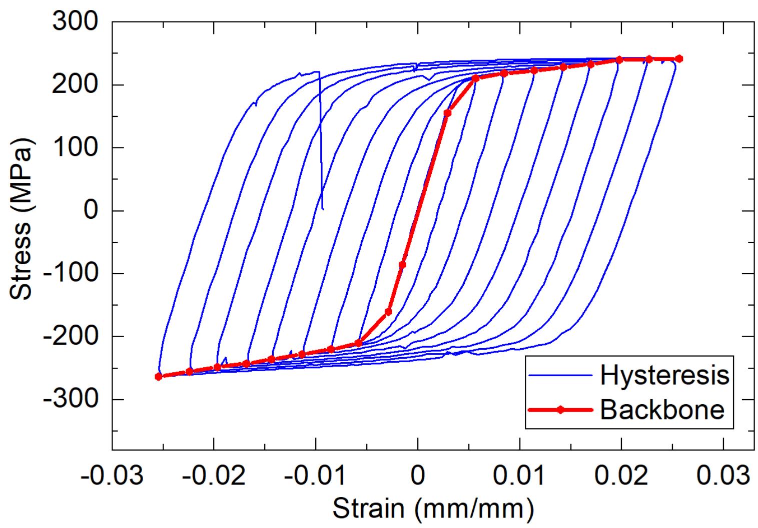

Figure 2. Hysteresis response and backbone curve of the specimen EA-NS-R1 [31]

The core was made of the aluminum alloy HS63S-T5, while the restraining member was made of the aluminum alloy A6061S-T6. The material properties of both the alloys are presented in the literature. A de-bonding material made of butyl rubber having a thickness of 1 mm has been used to reduce the friction between the core and the restraining member. Wang et al. [31] tested ten specimens under reversed cyclic loading. In this study, the backbone curve for the specimen EA-NS-R1 has been used and is shown in Figure 2. The details of the experiment can be found elsewhere.

3 DESCRIPTION OF STUDY BUILDING

The performance of extruded aluminum BRB on the seismic response of a braced frame structure has been analyzed. A 3-story benchmark building designed for the SAC project [34] has been adopted in this analysis. The building consists of three stories, each with a height of 3.96 meters, and features four bays in the East-West direction and six bays in the North-South direction. Each bay spans 9.14 meters from center to center. The plan and elevation of the study frame are shown in Figure 3.

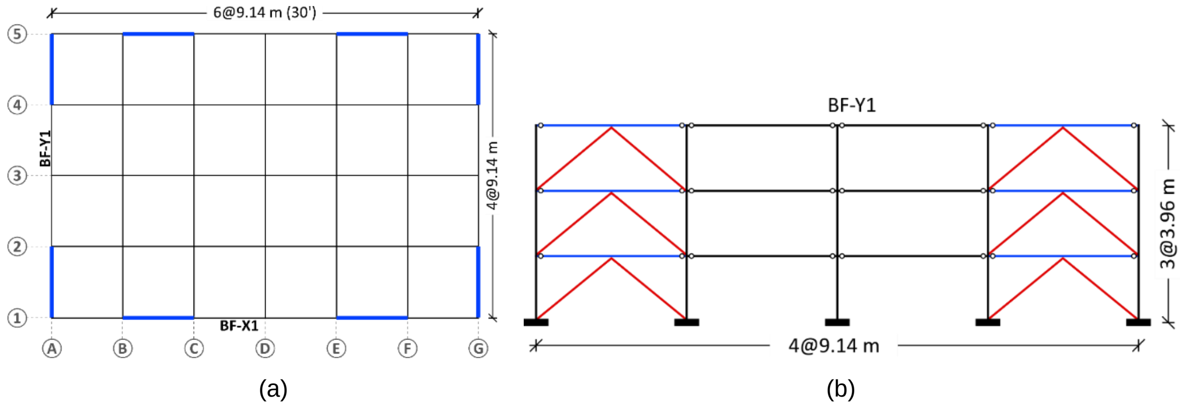

Figure 3. Plan and Elevation of the SAC 3-story frame.

The building is assumed to be located in Downtown Los Angeles with site Class D, deep stiff soil, Risk Category II, seismic source- Type A, and distance from seismic source < 2 km. The seismic weight of the building is calculated as 27645 kN.

4 CONFIGURATIONS AND DESIGN OF BRB

BRBs are provided in a Chevron configuration along the periphery of the first and last bays in the East-West direction. The Frame BF-Y1, shown in Figure 3b, illustrates the configuration of the BRBs. The Beam-column connections are assumed to be pinned. The loads are calculated according to ASCE/SEI- 7-16 [1] provisions, and design is carried out according to AISC 341-16 [35] and AISC 360-16 [36]. The design parameters are listed in Table 1, and the lateral shear along each story is shown in Figure 4.

DBE spectral response acceleration (0.2 s), S_{DS}	1.39 g
DBE spectral response acceleration (0.2 s), S_{D1}	0.77 g
Response reduction factor (R)	7
Seismic response co-efficient C_s	0.1985

Table 1. Design parameters based on seismicity data

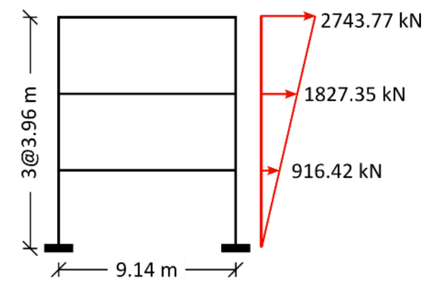

Figure 4. Vertical distribution of lateral shear

The entire lateral load is assumed to be resisted by the BRB, i.e., the lateral load in each story is resisted by four BRBs. A capacity-based approach is used for designing the frames, in which the capacity-limited forces are substituted in place of the lateral loads and BRBs. The capacity-limited loads are calculated as follows:

Ultimate tensile strength of the BRB,

$$P_{Tu} = \omega R_y F_{yc} A_c \tag{1}$$

Ultimate compressive strength of the BRB

$$P_{Cu} = \beta \omega R_y F_{yc} A_c \tag{2}$$

The values of the above parameters adopted in this study are presented in Table 2.

Parameter	Description	Value
ω	Strain-hardening adjustment factor	1.54
R_y	Ratio of the expected yield stress to the specified minimum yield stress	1.1
F_{yc}	Yield stress of the core material	203 MPa
A_c	Area of the core	-
β	Compression strength factor	1.04

Table 2. Parameters used in calculating the capacity-limited forces

The BRBs are removed, and the capacity-limited loads are applied to the frame shown in Figure 3b. The Member forces are thus calculated using ETABS Software and brace members are designed accordingly. The member sizes of the BRBF are shown in Figure 5.

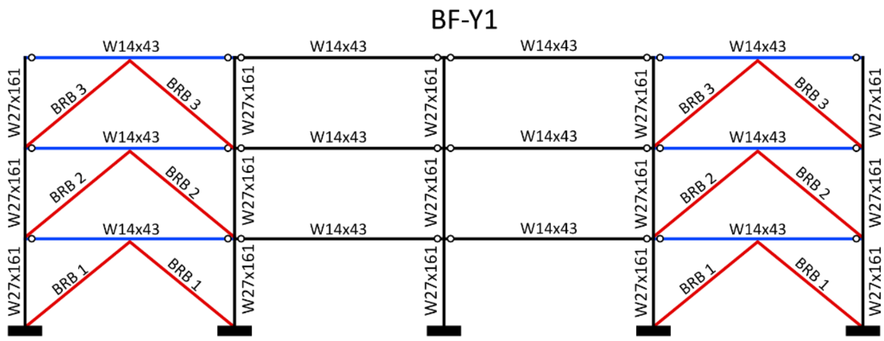

Figure 5. Member sections of the BRBF

5 MODELLING AND ANALYSIS OF BRBF

The Buckling Restrained Brace Frames (BRBFs) are modeled in the program *OpenSeesPy* [37]. The stress-strain behavior of the beam and columns are modeled using Steel01 elements, assuming a bilinear relationship. Whereas the stress-strain behavior of BRB is modeled using the HysteresisSM element, reproducing the backbone curve. The section properties are incorporated using a fiber section. BRB is modeled as a rectangular section with the cross-sectional area determined as mentioned in the previous section. The beam-column joints are assumed to be pinned. The OpenSees model is shown in Figure 6.

Figure 6. OpenSees model showing the Node numbers and Element numbers

The fundamental time period of the BRBF is computed as 0.7 s. Rayleigh damping of 5% is computed and applied to the frame using the first two time periods. The time-history analysis of the BRBF is performed using a total of twenty ground motions proposed by the SAC project. The response spectrum of these ground motions is given in Figure 7. The time history analysis is performed using the Newmark algorithm. The results are presented in the next section.

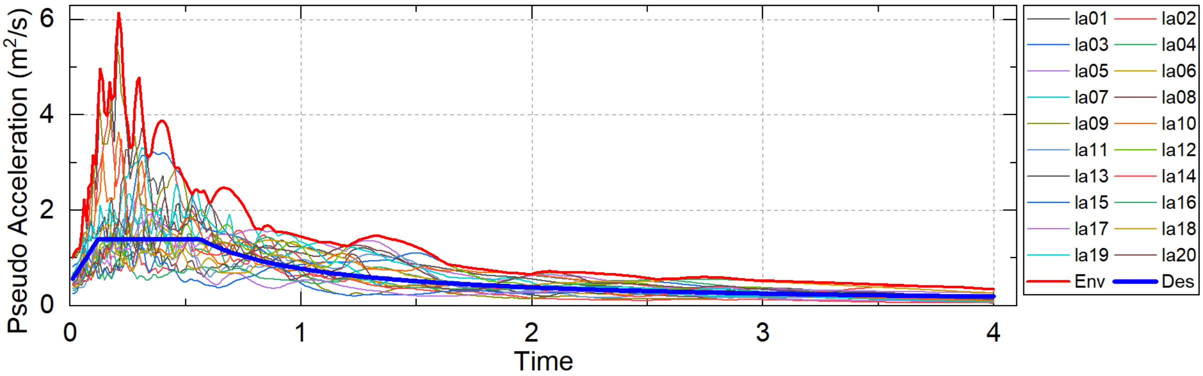

Figure 7. Response spectrum of the time histories and the Design Spectrum as per ASCE7-16 according to the site conditions

6 RESULTS

The results of the nonlinear time history analysis are presented in this section. The 3-story BRBF is subjected to twenty different ground motions representing the Design-basis Earthquake (DBE) hazard level. The displacement response of the roof (node 41 in Figure 6) is shown in Figure 8. The maximum displacement is 0.29 m. It can be observed from the response that the frame has sustained residual drift. The inter-story drift ratio (ISDR) and the residual drift ratio (RDR) are computed for each of the time histories. ISDR is the ratio between the maximum relative displacement between two stories to the height of the story. RDR is the ratio between the residual (at the end of analysis) relative displacement between two stories to the height of the story. These two parameters are used to evaluate the damage suffered by the BRBF. Figure 9 shows the ISDR and RDR of the BRBF subjected to the twenty earthquake time histories mentioned earlier.

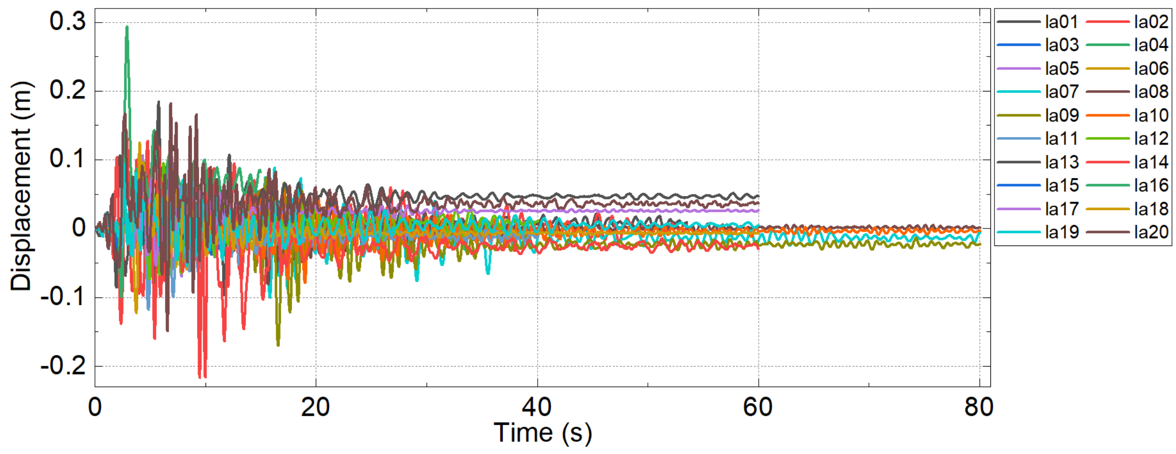

Figure 8. Displacement Time histories of the BRBF roof level

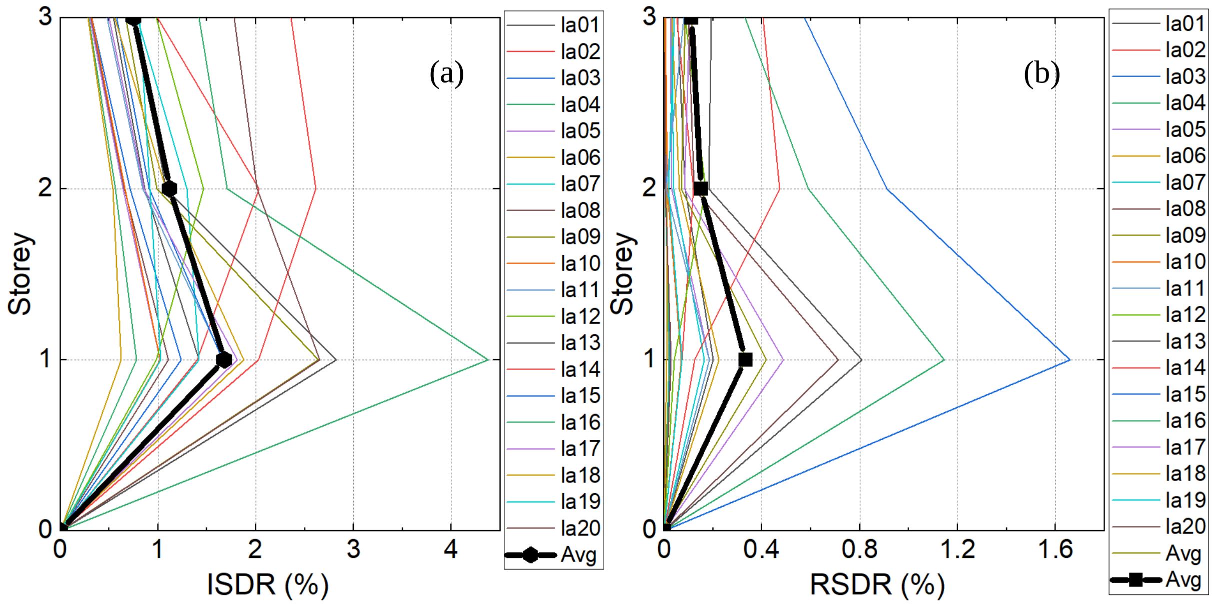

Figure 9. ISDR and RDR plots for the BRBF subjected to earthquake loadings

The maximum Interstory Drift Ratio (ISDR) of 4.38% is observed for la16 at the first floor of the BRBF. Besides, the maximum average ISDR is 1.68%, also observed at the first floor, which is less than 2%. Similar trends can be noted in the RDR response. The highest RDR recorded is 1.65% for la15 on the first floor, with the maximum average RDR being 0.33%, also found on the first floor.

7 CONCLUSIONS

A nonlinear time history analysis was performed on a Buckling Restrained Brace Frame (BRBF) subjected to 20 earthquake time histories at the Design Basis Earthquake (DBE) level. The results are presented through displacement time histories, Inter-storey Drift Ratios (ISDR), and Residual Drift Ratios (RDR). The analysis demonstrates that the performance of the aluminium buckling-restrained brace (BRB) is commendable, effectively reducing both the ISDR and RDR of the building. Furthermore, the performance of the aluminum BRB is on par with that of steel BRBs documented in the literature, suggesting it could be a better alternative.

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