Bulletin of
Civil Engineering
Vol. 5 No. 1, February 2025
Research Article

Investigation on Earthquake Performance of Reinforced Concrete Frames Strengthened with Different Buckling-restrained Braces Properties

Taufiq Ilham Maulana[a*]

[a] *Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia*

DOI: https://doi.org/10.18196/bce.v4i1.25925

Abstrak

Pengaku tahan tekuk (BRB) banyak digunakan untuk perkuatan seismik, namun kompromi kinerja antara kekakuan dan daktilitas rangka beton bertulang masih belum banyak dieksplorasi. Studi ini menyelidiki kinerja seismik rangka beton bertulang 10 lantai dengan 5 bentang, yang mematuhi standar Indonesia SNI 1726:2019 dan SNI 2847:2019 (ASCE 7-16 dan ACI 318-14), yang dipasang dengan dua konfigurasi BRB yang berbeda: (1) BRB dengan kekakuan awal yang besar tetapi daktilitas yang lebih rendah dan (2) BRB dengan kekakuan awal yang rendah tetapi daktilitas yang besar. Model nonlinier rangka 2D dibentuk dengan tinggi antar lantai 3 m dan panjang bentang 6 m. Elemen balok-kolom dimodelkan sebagai elemen garis dengan pegas geser dan lentur nonlinier, sementara BRB direpresentasikan menggunakan model histeresis bi-linear. Dua BRB dipasang di panel ke-2 dan ke-4 dari 5 panel, menargetkan lantai dengan pergeseran antar lantai yang tinggi. Sebelas gerakan tanah yang disesuaikan dengan spektrum diskalakan ke kondisi geografis Indonesia untuk mengevaluasi respons seismik. Parameter yang ditinjau mencakup pergeseran antar lantai dan perilaku gaya-perpindahan BRB. Hasil menunjukkan bahwa BRB dengan kekakuan awal yang kuat secara efektif mengurangi pergeseran antar lantai puncak dibandingkan dengan BRB dengan kekakuan lemah. Namun, BRB dengan kekakuan lemah mencapai daktilitas kumulatif yang lebih besar. Kedua jenis BRB tetap mengurangi kerusakan structural namun memiliki karakter khas masing-masing. Studi ini secara unik menunjukkan barter input kekakuan dan daktilitas pada bangunan tinggi, bahwa BRB dengan kekakuan kuat mengutamakan pengendalian pergeseran langsung, sementara BRB dengan kekakuan lemah berdeformasi lebih setelah kondisi leleh.

Kata-kata kunci: performa seismik, gedung beton bertulang, studi parametrik, pengaku tahan tekuk.

Abstract

Buckling-restrained braces (BRBs) are widely adopted for seismic retrofitting, yet the performance trade-offs between stiffness and ductility in high-rise reinforced concrete (RC) frames under region-specific seismic conditions remain underexplored. This study investigates the seismic performance of a 10-story, 5-bay reinforced concrete (RC) frame, complying with Indonesian standards SNI 1726:2019 and SNI 2847:2019 (ASCE 7-16 and ACI 318-14), retrofitted with two distinct buckling-restrained brace (BRB) configurations: (1) BRB with large initial stiffness but less ductility and (2) BRB with low initial stiffness but enhanced ductility. A 2D nonlinear model of the RC frame was developed, featuring 3 m inter-story heights and 6 m span bays. Beam-column elements were modeled as line elements with nonlinear shear and bending springs, while BRBs were represented using a bi-linear hysteresis model. Two BRBs were installed in bays 2 and 4, targeting stories with elevated inter-story drift. Eleven spectrum-matched ground motions were scaled to Indonesian geographical conditions to evaluate seismic responses. Key performance metrics included inter-story drift response and BRB force-displacement behavior. Results demonstrated that BRB with large initial stiffness effectively reduces peak inter-story displacement compared to BRB with weak stiffness. However, BRB with weak stiffness achieves greater cumulative ductility. Both types of BRB still reduce structural damage but have their unique characteristics. The study uniquely quantifies the stiffness-ductility trade-off in high-rises, demonstrating that large-stiffness BRBs prioritize immediate drift control, while weak-stiffness BRBs enhance post-yield stability.

Keywords: Seismic performance, reinforced concrete building, parametric study, buckling-restrained brace

Article History
Received
1 Februari 2025

Revised
14 Februari 2025

Accepted
26 Februari 2025

*Correspondence Author
taufiq.im@ft.umy.ac.id

1 INTRODUCTION

In regions of high seismic activity, such as Indonesia, the resilience of reinforced concrete (RC) structures against earthquakes remains a critical concern for engineers and policymakers. Reinforced concrete frames, while widely used for their cost-effectiveness and adaptability, often require retrofitting to meet modern seismic demands, particularly in older high-rise buildings. Buckling-restrained braces (BRBs) have emerged as a prominent solution for enhancing lateral stiffness and energy dissipation in such structures. Unlike conventional braces, BRBs mitigate global buckling, enabling stable hysteretic behavior under cyclic loading (Dunn & Pantelides, 2022; Mohebi et al., 2023). Studies have demonstrated their effectiveness in improving the seismic performance of RC frames, especially in structures with vertical irregularities or curtailed walls (Maulana et al., 2022, 2023; Maulana & Syamsi, 2023). Despite their proven efficacy, the design of BRBs involves inherent trade-offs between initial stiffness and ductility or can be understood as a balance that remains inadequately quantified for high-rise RC frames subjected to region-specific seismic hazards.

Existing studies have extensively documented the benefits of BRBs in low-to mid-rise steel structures, emphasizing their ability to control inter-story drift and dissipate energy (Castaldo et al., 2021; Freddi et al., 2021). However, applying BRBs in high-rise RC frames, particularly under the complex seismic conditions of archipelagic regions like Indonesia, introduces unique challenges. For instance, the optimization of BRB placement in RC frames with curtailed walls has been shown to significantly enhance seismic performance, though the effectiveness varies with structural configurations and ground motion characteristics (Maulana et al., 2023; Maulana & Syamsi, 2023). The dynamic response of taller structures and variations in ground motion characteristics necessitate a nuanced understanding of how BRB properties influence overall performance. While stiff BRBs may effectively limit peak displacements, they risk concentrating damage in critical elements due to reduced ductility (Bai et al., 2022). Conversely, ductile BRBs may enhance post-yield stability but allow higher initial drifts, potentially compromising non-structural components (Li et al., 2023). This dichotomy underscores the need to evaluate BRB configurations in contextually relevant frameworks, aligning with localized design standards and seismic spectra.

This study investigates the seismic performance of a 10-story RC frame retrofitted with two distinct BRB configurations: (1) high initial stiffness with limited ductility and (2) low initial stiffness with enhanced ductility. The two BRB types, stiff and ductile, were selected to represent distinct retrofit strategies with contrasting seismic performance characteristics. The stiff BRB reflects a design approach aimed at minimizing immediate drift and enhancing structural rigidity, which is beneficial for operational continuity. In contrast, the ductile BRB emphasizes energy dissipation capacity and deformation tolerance, making it suitable for structures where damage control and resilience under strong shaking are prioritized. This comparison allows for a better understanding of how different BRB properties influence retrofitted building behavior under seismic loading.

Compliant with Indonesian seismic design codes (SNI 1726:2019 and SNI 2847:2019, adapted from ASCE 7-16 and ACI 318-14), the analysis employs a nonlinear 2D model subjected to spectrum-matched ground motions representative of Indonesian geological conditions. The research quantifies key metrics, inter-story drift, and BRB force-displacement behavior to assess how stiffness-ductility trade-offs influence structural safety and retrofitting efficacy. Results demonstrate that BRBs with large initial stiffness effectively reduce peak inter-story displacement, while those with weak stiffness exhibit more favorable hysteretic energy dissipation characteristics.

By bridging the gap between theoretical BRB advantages and practical high-rise retrofitting challenges, this work provides actionable insights for engineers prioritizing immediate drift control or enhanced energy dissipation. The findings contribute to a deeper understanding of performance-based design strategies in regions prone to frequent, high-intensity earthquakes, offering a framework to optimize BRB properties for Indonesia's unique seismic landscape.(Maulana, 2022; Maulana et al., 2023)

2 RESEARCH METHOD

2.1 Idealization Modelling of Structural Elements

The numerical analysis was chosen to conduct the study. The behaviors of buildings under earthquake were inspected by evaluating the seismic response of the structural element and story movement. This study uses STERA_3D, an open-source software developed by a Japanese professor (Saito, 2020), because it is capable of modeling the nonlinear behavior of structural components such as beams, columns, and buckling-restrained braces (BRBs).

In STERA_3D software, a beam is modeled as a line element with two nonlinear flexural springs at both ends and one nonlinear shear spring at the center. The axial springs for the column element were modeled by adapting Multi-spring models (MSA) (Lai, S. -S.; Will, G.T.; Otani, 1984). For the BRBs element, the bilinear model was adapted to catch the behavior after yielding. The details of the idealization are described in the software technical manual (Saito, 2020).

2.2 Building Specimens

Three reinforced concrete frame buildings were evaluated in this research. All specimens have 10 stories with five bays, portraying the mid- to high-rise buildings in a high seismicity region in Indonesia and complying with the current local building code (SNI 1726:2019, SNI 2847:2019). The modeling and design approaches employed in this study adhere to the relevant provisions of SNI 1726:2019 for seismic design, ACI 318-19 for concrete structures, and ASCE 7-16 for minimum design loads. Specifically, the seismic demand and performance objectives were assessed in accordance with SNI 1726, ensuring consistency with local seismic hazard assessments. Detailing and capacity design principles followed ACI 318 guidelines to ensure adequate ductility and strength. Additionally, BRB performance was evaluated considering the load resistance and factor design (LRFD) framework as outlined in ASCE 7-16. This compliance ensures that the proposed retrofit strategies meet both local and international standards for safety and performance. Although STERA_3D supports three-dimensional modeling, a two-dimensional model was adopted in this study to simplify the analysis and reduce computational time. This simplification remains sufficient to capture the essential building responses relevant to the study's objectives. The building is located in Bantul, a special province of Yogyakarta. Since the limitation of soil investigation, in this study, the average shear wave velocity at the first 30 m top layer (Vs30) was investigated based on the global hybrid Vs30 map developed from topographic-slope and regional insets retrieved from USGS (Heath et al., 2020). Figure 1 depicts the value of Vs30 in the Bantul region. The investigation shows that the Vs30 value at the selected location is 259 m/s, where it is between 175 – 350 m/s. Thus, the soil classification type is D (stiff soil).

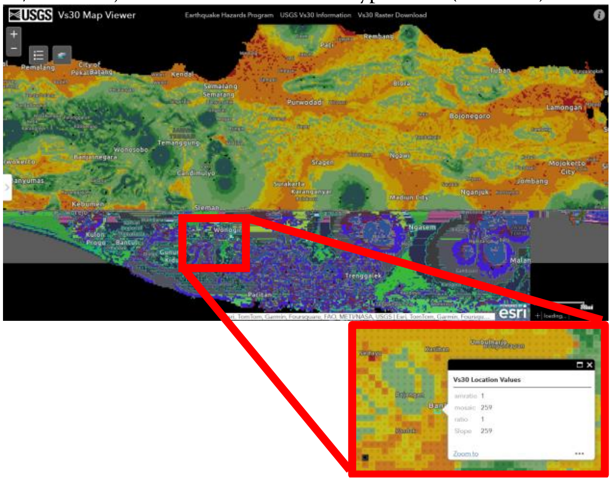

Figure 1 Vs_{30} value at Bantul region (Heath et al., 2020)

The building has a 3-meter inter-story height and a 6-meter span length. The beam size and the column size geometry are 300 × 600 mm² and 600 × 600 mm², respectively, with the compressive concrete strength being 24 MPa as normal concrete. The longitudinal reinforcing rebars at the beam and column are 4D22 mm and 8D22 mm, with the shear reinforcing rebars 2D13-100 mm and 2D13-150 mm, respectively, where the yielding rebar tension strength is 400 MPa. A two-dimensional model was developed to simplify the analysis, and the seismic input is only uniaxial at the x direction. Figure 2 presents the 2D model of the specimen without BRBs. From the modal analysis shown in Figure 3, the first mode of the building without improvement is 0.973 seconds (referred as T_{upper}), with T_{lower} is achieved at mode 11 with 0.0338 seconds.

The BRB elements are installed at the levels that exhibit a large amount of inter-story drift at levels 4 and 5 and selected at bay number 2 and 4. Two BRBs are employed at each level, and the two building specimens have different properties, indicating the large initial stiffness with low ductility and the low initial stiffness with high ductility, as shown in Figure 4. The initial stiffness (K_0), the stiffness after yielding (depicted as K_1/K_0), and the yielding shear force for the BRB elements are 30 kN/mm, 0.02, 500 kN for specimen 1 and 15 kN/mm, 0.02, 250 kN for specimen 2.

2.3 Input Strong Ground Motion and Characteristic

The strong ground motions were selected carefully based on three seismic source types: megathrust, Benioff, and shallow crustal (Pusat Studi Gempa Nasional, 2022). The response spectrum characteristic at the Bantul region has T_0, T_s, S_{DS}, S_{D1} values of 0.15 sec., 0.73 sec., 0.92 g., and 0.67 g. respectively. Since the first natural period of the normal building specimen (0.973 sec.) is larger than the T_s value, thus the source distance and the earthquake magnitude map read in the earthquake hazard map is S_a 3.0 sec. Table 1 shows the recapitulation of magnitudes and source distances of each seismic source type based on the Indonesian earthquake hazard map.

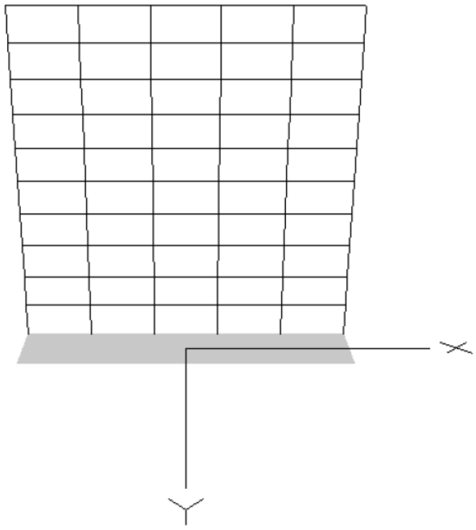

Figure 2 Two-dimension model of building specimen

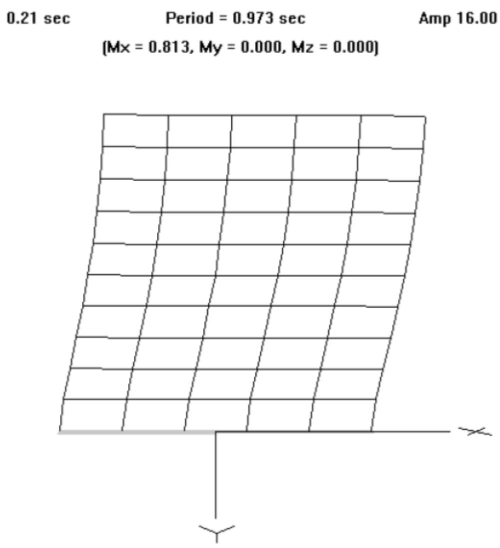

Figure 3 First mode sway of building specimen

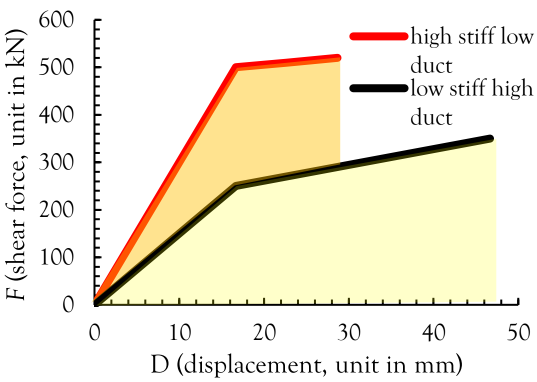

Figure 4 BRBs idealization of BRBs for two specimen

Table 1 Magnitudes and source distances for S_a 3.0 sec.

Source type	Magnitude range (in M)	Source distance range (in km)
Shallow crustal	6.2 – 6.6	10 – 30
Benioff	7.2 – 9.0	100 – 150
Megathrust	7.8 – 9.0	70 - 120

After some careful selection of range, each source type ranges were inputted to PEER Strong Ground Motion (PEER, 2021) to obtain the seismic wave having the similar characteristic to the selected geographical property. Eleven uniaxial strong ground motions were retrieved and their original response spectrums were matched to the Bantul region spectrum. Figure 5 showed the matched response spectrum and the average spectrum of eleven individual matched spectrum. The average spectrum were matched in between 0.8 T_{lower} and 1.2 T_{upper} and having tolerance of 10% as inquired in SNI 1726:2019. Table 2 showed the detail of the selected earthquake ground motion properties.

Table 2 Details of selected original strong ground motion characteristics

RSN No.	Duration (sec)	Eq. Name	Year	Station	M.	Mechanism	dist. (km)	Vs30 (m/s)	dir. X (°)	dir. Y (°)
876	25.6	"Landers"	1992	"La Habra - Briarcliff"	7.28	strike slip	143.12	338.27	000	090
853	26.9	"Landers"	1992	"El Monte - Fairview Av"	7.28	strike slip	135.88	290.63	095	085
849	27.6	"Landers"	1992	"Covina - W Badillo"	7.28	strike slip	128.06	324.79	000	070
5886	31.3	"El Mayor-Cucapah_ Mexico"	2010	"Indian Wells - Hwy111 & El Dorad"	7.2	strike slip	130.72	311.18	360	090
12	33.5	"Kern County"	1952	"LA - Hollywood Stor FF"	7.36	Reverse	117.75	316.46	090	080
834	35.2	"Landers"	1992	"Arcadia - Arcadia Av"	7.28	strike slip	137.25	330.5	172	062
6007	39.8	"El Mayor-Cucapah_ Mexico"	2010	"Indio - Jackson Road"	7.2	strike slip	128.69	292.12	180	070

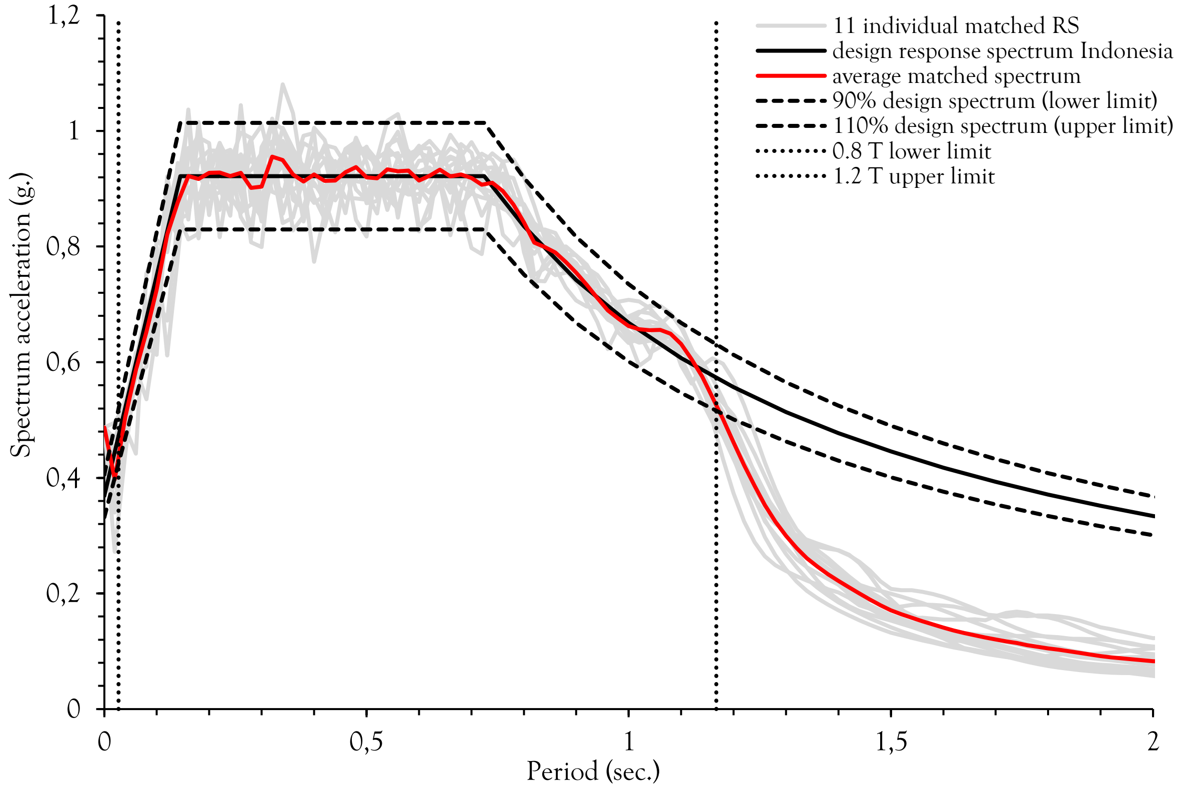

Figure 5 Matched response spectrums of selected strong ground motions

3 RESULTS AND DISCUSSIONS

3.1 Inter-story drift responses of normal building (without BRBs)

To determine where the BRBs were installed and how much BRBs were needed, the inter-story drift (ISD) response of normal building specimen were first inspected. In this paper, only 3 seismic inputs were shown as the result for simplification, namely RSN 834-172, RSN 853-095, and RSN 876-000. Figure 6 showed the ISD along the height. From the results, although the drift is still less than 1% (3 cm) of the inter-story height, it is known that level 4 and level 5 exhibited the largest amount of drift compared to other level. This result is similar to the first mode shape as the failure pattern followed the mode shape at Figure 3. Thus, in this study, BRBs were selected to be installed at level 4 and 5.

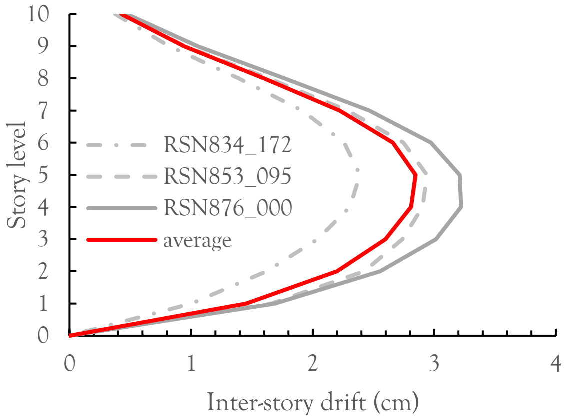

Figure 6 Inter-story drift response of normal bare frame

3.2 Inter-story drift responses of improved building with large initial stiffness and lower ductility

The first trial was installing BRBs having larger initial stiffness and having lower ductility. Since it has bigger initial stiffness of BRBs, the shear force at story level 4 and 5 were supported by both BRBs and the RC frame. However, since the initial stiffness is too large, the ISD at level 4 and 5 were far less than the normal result (about 2 cm). Since the ISD at all story level still less than 1%, due to excessive stiffness contrast, building specimen 1 potentially inducing irregular behavior, where the further inspection is needed. Figure 7 illustrated the result of ISD for specimen 1.

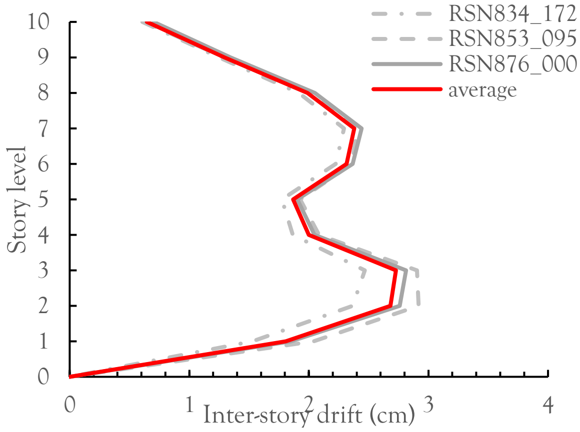

Figure 7 Inter-story drift response of specimen 1

3.3 Inter-story drift responses of improved building with low initial stiffness and large ductility

The second trial was installing BRBs having small initial stiffness and higher ductility. Similar to specimen 1, the shear force at story level 4 and 5 were both supported by BRBs and the RC frame. Nevertheless, the initial stiffness is weaker than specimen 1, so the ISD at level 4 and 5 were not far less than the normal result (about 2.5 cm). The ISD at all story level is than 1%, and there is no large deviation for each story compared to specimen 1. Figure 8 showed the ISD for specimen 2.

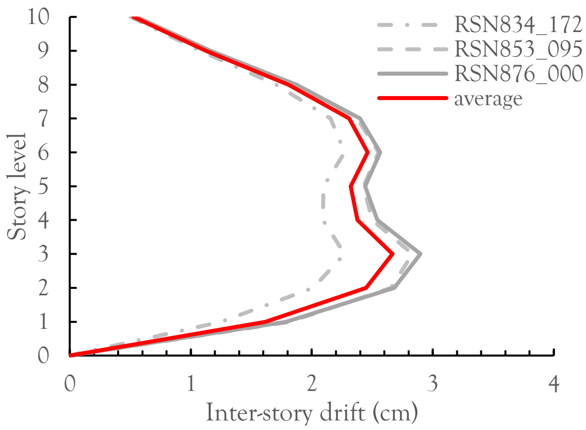

Figure 8 Inter-story drift response of specimen 2

3.4 Comparison of BRBs hysteresis response for both specimens

BRBs structural element nonlinear response were outputted from STERA_3D program to have better understanding about the seismic behavioral responses. Figure 9 depicted the Force-displacement relationship of BRB at level 4 for specimen 1 and specimen 2 against seismic RSN 834-172. Red line showed the specimen 1 where it has high initial stiffness and entered the nonlinearity. After the yielding point, the BRBs was entering the yielding stage and forming yielding drift and having small area of energy dissipation. This is different to specimen number 2 which was entering the yielding stage earlier at 250 kN and thus exhibiting large drift and having larger area of energy dissipation. Both response are acceptable in terms of energy absorption since both entered nonlinear stage and still conforming the current local building and seismic codes.

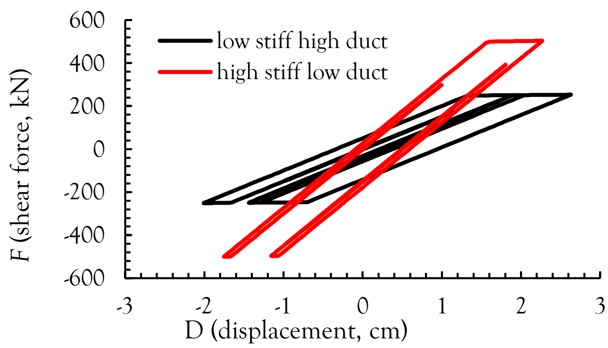

Figure 9 Hysteretic loop of BRBs at Level 4, Bays 2, under RSN 834_172

From a practical perspective, the findings suggest that the choice between stiff and ductile BRBs should be aligned with the specific performance objectives of a retrofit project. For instance, stiff BRBs may be preferable for buildings where limiting immediate drift is critical, such as hospitals or emergency facilities, while ductile BRBs may be more suitable for structures requiring enhanced energy dissipation capacity under severe seismic events. These insights can inform tailored retrofit strategies in performance-based seismic design frameworks.

4 CONCLUSIONS

This study provides critical insights into the stiffness-ductility trade-offs of buckling-restrained braces (BRBs) when retrofitting high-rise reinforced concrete (RC) frames under region-specific seismic conditions in Indonesia. By analyzing a 10-story RC frame retrofitted with two BRB configurations: high initial stiffness (Specimen 1) and enhanced ductility (Specimen 2), the research demonstrates that BRBs with large initial stiffness effectively reduce peak inter-story drift compared to conventional frames, prioritizing immediate displacement control. In contrast, BRBs with lower initial stiffness exhibit superior cumulative ductility and energy dissipation, achieving larger hysteretic loops despite marginally higher drifts. Both configurations complying with Indonesian design codes (SNI 1726:2019, SNI 2847:2019) and maintain inter-story drift below 1%, underscoring their viability for seismic retrofitting. The nonlinear 2D modeling, validated through spectrum-matched ground motions representative of Bantul's geological conditions, highlights the importance of aligning BRB properties with performance objectives: large-stiffness BRBs mitigate peak demands in critical stories, while weak-stiffness BRBs enhance post-yield stability, crucial for long-duration shaking common in archipelagic regions. While the findings provide valuable insights into the building's response, it is important to note that the use of a two-dimensional model represents a simplification. This limitation may influence certain aspects of the structural behavior that would be better captured in a full three-dimensional analysis.

These findings offer actionable guidance for engineers balancing immediate drift control against long-term energy dissipation in high-rise RC retrofits. For Indonesian seismic landscapes, where megathrust, Benioff, and crustal sources impose diverse demands, Specimen 1 is optimal for structures prioritizing occupant safety via strict drift limits, while Specimen 2 suits systems requiring robustness under repeated cyclic loading. The study advances performance-based design by quantifying trade-offs often overlooked in code-based approaches, particularly for high-rises on stiff soils. Future researches should explore 3D modeling, soil-structure interaction, cost-benefit analyses, multi-story retrofit strategies, and experimental validation to refine BRB deployment. By contextualizing BRB design within Indonesia's unique seismic framework, this research contributes a scalable methodology for similar high-risk regions, bridging global retrofitting practices with localized structural demands.

5 ACKNOWLEDGEMENT

The author would like to acknowledge Professor Taiki Saito for the developing STERA_3D program and the Universitas Muhammadiyah Yogyakarta for supporting the research.

6 REFERENCES

Bai, J., Li, W., Chen, H., Feng, M. Q., & Wang, Y.-H. (2022). A Stiffness Ratio-Based Seismic Design for Reinforced Concrete Frames with Buckling-Restrained Braces. *International Journal of Structural Stability and Dynamics*. https://doi.org/10.1142/s0219455422400053

Castaldo, P., Tubaldi, E., Selvi, F., & Gioiella, L. (2021). Seismic performance of an existing RC structure retrofitted with buckling restrained braces. *Journal of Building Engineering*, *33*, 101688. https://doi.org/10.1016/J.JOBE.2020.101688

Dunn, J. D., & Pantelides, C. P. (2022). Seismic Retrofit of Reinforced Concrete Moment Frame Using a BRB with U-Plate Connections. *Journal of Structural Engineering-Asce*, *148*(9). https://doi.org/10.1061/(asce)st.1943-541x.0003408

Freddi, F., Tubaldi, E., Zona, A., & Dall'Asta, A. (2021). Seismic performance of dual systems coupling moment-resisting and buckling-restrained braced frames. *Earthquake Engineering & Structural Dynamics*, *50*(2), 329–353. https://doi.org/10.1002/EQE.3332

Heath, D. C., Wald, D. J., Worden, C. B., Thompson, E. M., & Smoczyk, G. M. (2020). A global hybrid VS 30 map with a topographic slope–based default and regional map insets. *Earthquake Spectra*, *36*(3), 1570–1584.

Lai, S. -S.; Will, G.T.; Otani, S. (1984). Model for Inelastic Biaxial Bending of Concrete Members. *Journal of Structural Engineering*, *110*, 2563–2584.

Li, G., Li, J., Fang, C., & Wang, Z. (2023). Seismic performance of two-story three-bay reinforced concrete frame equipped with K-configured buckling restrained braces. *Journal of Building Engineering*, *74*, 106904. https://doi.org/10.1016/j.jobe.2023.106904

Maulana, T. I. (2022). *Seismic Performance Assessment and Improvement of Reinforced Concrete Buildings with Vertical Irregularity (鉛直方向の不整形成を有する鉄筋コンクリート造建物の耐震性能評価と性能改善)* [Dissertation]. Toyohashi University of Technology.

Maulana, T. I., Fonseca, P. A. de F., & Saito, T. (2022). Application of genetic algorithm to optimize location of BRB for reinforced concrete frame with curtailed shear wall. *Applied Sciences*, *12*(5), 2423.

Maulana, T. I., & Syamsi, M. I. (2023). Seismic performance improvement of reinforced concrete frame with vertical irregularity using buckling-restrained braces. *AIP Conference Proceedings*, *2846*(1).

Maulana, T. I., Syamsi, M. I., & Majima, R. (2023). Optimum buckling-restrained braces application to enhance seismic performance of RC frame with curtailed walls. *E3S Web of Conferences*, *429*, 05029. https://doi.org/10.1051/e3sconf/202342905029

Mohebi, B., Sartipi, M., & Kazemi, F. (2023). Enhancing seismic performance of buckling-restrained brace frames equipped with innovative bracing systems. *Archives of Civil and Mechanical Engineering*, *23*. https://doi.org/10.1007/s43452-023-00779-4

PEER. (2021). *PEER (Pacific Earthquake Engineering Center). Ground Motion Database*.

Pusat Studi Gempa Nasional. (2022). Peta Deagregasi Bahaya Gempa Indonesia Untuk Perencanaan dan Evaluasi Infrastruktur Tahan Gempa. *Jakarta: Direktorat Bina Teknik Permukiman Dan Perumahan*.

Saito, T. (2020). *Structural Earthquake Response Analysis, STERA_3D Version 10.8*. http://www.rc.ace.tut.ac.jp/saito/software-e.html