Performance-Based Retrofitting of Aging RC Frames Using Innovative Knee-Braced Buckling-Restrained Braces for Enhanced Seismic Resilience

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ABSTRACT. The performance of reinforced concrete (RC) structures is a critical area of research, given the increasing need for resilient infrastructure in seismically active regions. Deficient RC frames, commonly found in aging buildings, exhibit limited ductility and energy dissipation capacity, rendering them vulnerable to seismic events. Currently, the literature lacks a study regarding the performance of knee-braced buckling-restrained braces (KBRBs) as a strengthening technique for deficient RC frames. Unlike traditional bracing systems, KBRBs offer enhanced energy dissipation and deformation capacity, eliminating the drawbacks associated with brace buckling. The motivation for this study stems from the need to develop innovative retrofit strategies that can enhance the seismic resilience of deficient reinforced-concrete frames while overcoming their inherent shortcomings. This study examines the seismic behavior of deficient reinforced-concrete frames strengthened with knee-braced, buckling-restrained brace systems using numerical analysis. By evaluating the energy dissipation and displacement demand of the strengthened frames, the study seeks to provide insights into the efficacy of KBRBs as a retrofitting solution. The significance of this research lies in tackling a key gap in retrofit strategies for vulnerable reinforced-concrete structures and introducing a promising approach for improving the seismic performance of deficient frames. The findings from this study will contribute to the development of performance-based design guidelines, enabling engineers to select effective retrofitting strategies that safeguard infrastructure in earthquake-prone regions.

Keywords: *Knee-Braced Buckling-Restrained Braces (KBRBs); Seismic Retrofitting, Deficient Reinforced Concrete Frames; Energy Dissipation, Numerical Dynamic Analysis; Seismic Resilience*

1 INTRODUCTION

The seismic vulnerability of reinforced concrete (RC) frames, especially in earthquake-prone areas, remains a pressing concern in structural engineering. Aging buildings often suffer from limited ductility and energy dissipation capabilities, increasing their risk of severe damage during seismic events. Consequently, retrofitting strategies have been extensively explored to improve their seismic resilience [1,2]

Buckling-restrained braces (BRBs) have emerged as an innovative solution to enhance the seismic performance of deficient RC frames. Unlike conventional bracing systems, BRBs are designed to prevent buckling under compressive forces, allowing significant axial deformation without loss of structural integrity [3,4]. Since their initial application in Japan in the late 1980s, BRBs have been increasingly adopted for their capacity to improve energy dissipation and reduce displacement demands under seismic loading [5,6].

The use of advanced materials and configurations has further expanded the potential of BRBs. For instance, shape memory alloy (SMA) BRBs have shown improved performance under moderate seismic conditions compared to traditional steel BRBs, particularly in controlling residual drift ratios [7]. Innovations like sliding gusset connections and short-yielding core BRBs have also demonstrated enhanced seismic resilience, minimizing interaction forces and improving the overall performance of RC frames [8,9].

The studies [10–13] collectively highlight the effectiveness of buckling-restrained braces (BRBs) in enhancing the seismic performance of reinforced concrete (RC) frames. Shake-table tests on BRB-strengthened frames consistently demonstrate significant improvements in lateral stiffness and strength compared to control frames without strengthening. For instance, BRBs increased stiffness by up to 70%, reduced lateral story drift by 46%, and maintained higher post-crack stiffness under severe ground-shaking scenarios. Novel BRB designs, such as those with innovative end parts or repairable circular steel cores, exhibit high ductility (e.g., μ=4) and stable hysteretic behavior under cyclic loading. Additionally, these systems effectively reduce displacement demands and protect critical regions, as evidenced by a 215% increase in lateral force resistance and the prevention of plastic hinge formation in strengthened frames during high-intensity seismic events. The integration of experimental and finite element analyses further validates the practical applicability of these systems, providing valuable insights into their design, fabrication, and performance in seismic retrofitting.

The studies [16,17] evaluates the seismic performance of knee-braced frames (KBFs) using steel and NiTi buckling-restrained braces (BRBs). Knee braces (KBs), positioned near beam-to-column connections, offer

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advantages such as space efficiency, minimal architectural disruption, and ease of installation and replacement compared to other brace types. Two types of KBs were fabricated by machining raw bars into a bamboo shape, and cyclic loading tests on reduced-scale specimens revealed stable cyclic properties for both KBs. Steel BRBs exhibited typical elasto-plastic hysteresis, while NiTi BRBs displayed flag-shaped hysteresis.

Despite the advancements in BRB technology, optimal configurations for specific applications remain an area of active research. The diverse shapes and designs implemented in real-life projects underscore the need for further investigation into the most effective configurations for maximizing seismic resilience [18]. This study aims to investigate the seismic performance of deficient RC frames strengthened with knee-braced buckling-restrained braces (KBRBs) through comprehensive numerical analyses. By focusing on Vancouver, Canada, a region with notable seismic activity due to the Cascadia Subduction Zone, this research is positioned to test the effectiveness of KBRBs in one of the most demanding urban environments. The evaluation of energy dissipation and displacement demands provides insights into the efficiency of KBRBs as a retrofitting solution. The findings aim to inform the development of performance-based design guidelines, facilitating the selection of effective retrofitting strategies to enhance seismic resilience in earthquake-prone regions.

2 RESEARCH METHODOLOGY

2.1 Prototype Frames

A 10-story deficient reinforced-concrete (RC) frame structure (Figure 1) was selected as the case study to assess the seismic performance of frames retrofitted with KBRBs. The prototype building has plan dimensions of 35 m × 35 m and a uniform story height of 3.5 m. The RC members were designed using concrete with a compressive strength of C40 (40 MPa) and deformed high-strength steel reinforcement with a minimum yield strength of 460 N/mm², consistent with ASTM A615M specifications.

For the KBRB evaluation, the braces were arranged in several configurations to examine how their placement influences the seismic behavior of the deficient RC frame. Three retrofit scenarios were considered (Figure 2). In the first scenario, the KBRBs were installed in the center bay of the frame (C cases). The second scenario placed the braces solely at the exterior bays (E cases), while the third scenario combined both approaches by installing KBRBs in the center and exterior bays (EC cases). These setups were selected to investigate how varying the number and location of restrained bays affects the overall seismic response.

The reference frame was intentionally selected in its deficient state, as it had been originally designed for gravity loads only. Its limited seismic capacity was confirmed through evaluation against the Canadian Earthquake Code, which demonstrated noncompliance under lateral loading. To ensure consistency in the comparison, the beams and columns were optimized using W-sections in accordance with AISC 360-22, while the KBRB sections were kept identical across all scenarios. The seismic response was assessed under multiple load cases, including dead, live, modal, gravity, and acceleration loads, to provide a comprehensive understanding of the structural performance for each configuration.

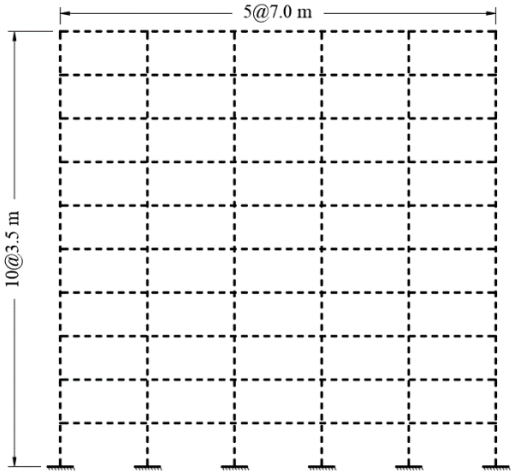


Figure 1. Reference frame (elevation view)

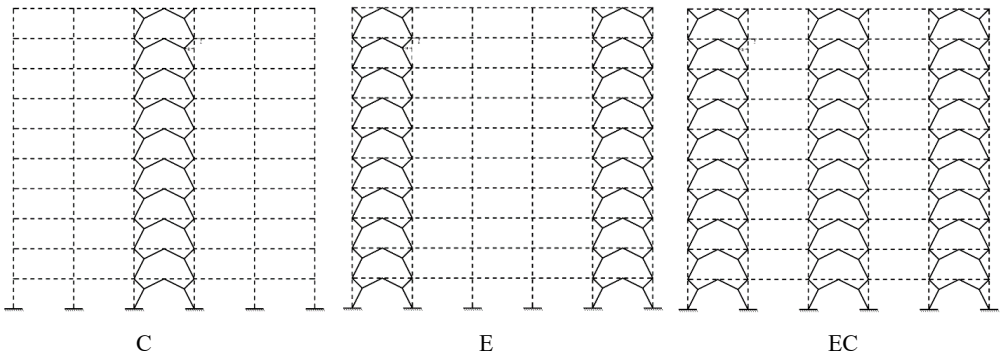


Figure 2. Configuration of different studied frames equipped with buckling-restrained braces

2.2 Frame Design

The frame was modeled as a three-dimensional system in ETABS 21 [19] and initially designed solely for gravity loads, adhering to the AISC 360-22 [20] guidelines. This design approach was chosen to establish the frame as deficient when subjected to seismic forces. Uniformly distributed dead loads of 35 kN/m and live loads of 20 kN/m were applied across all beams in the direction of gravity. Following this, a linear elastic analysis was conducted on the beams and columns using the equivalent lateral force method outlined in NBCC [21], confirming the frame's inadequacy in resisting seismic actions and highlighting the need for retrofitting. The factors and parameters used for calculating the lateral loads are listed in Table 1.

Table 1. Seismic Design Parameters for Equivalent Static Analysis.

Parameter	Value	Unit
PGA	0.4	/g*
Sa(0.2)	0.95	/g
Sa(0.5)	0.64	/g
Sa(1.0)	0.33	/g
Sa(2.0)	0.18	/g
Sa(4.0)	0.18	/g
Site class	C	-
Fa	1	-
Fv	1	-
Mv	1	-
Rd	5	-
Ro	1.5	-
*g: gravity acceleration = 9.81 m/s$_2$.		

2.3 Numerical Modeling of Buckling-Restrained Braces

The StartBRB-30.0, developed by Star Seismic BRB, is a specialized component chosen for its high seismic resilience, selected through an iterative design process to ensure compliance with the equivalent lateral load method of the adopted seismic code. Its key features include a robust yielding core and elastic segments, enhancing the frame's capacity to resist seismic forces effectively.

The yielding core, with an area of 193.5 cm², is designed to undergo plastic deformation, dissipating seismic energy and reducing structural stress. The elastic segment has a stiffness of 5,062,740.2 kN/m, allowing significant elastic recovery. The yielding core and elastic segment measure 4.2672 m and 2.4274 m, respectively, providing a balanced combination of flexibility and stability. Yield strengths in tension and compression are 5,938.4 kN and 5,871.7 kN, while the maximum strengths reach 7,005.9 kN and 6,939.2 kN, highlighting the component's capacity to withstand substantial loads during seismic events.

The nonlinear modeling followed the guidelines of NIST GCR 17 [22], utilizing inelastic hinges for beam and

column nonlinearities as defined by ASCE 41-17. BRB sections were represented as link elements to accurately capture their nonlinear behavior. Rayleigh damping, with a 2.5% damping ratio, was employed in the direct integration analysis, targeting periods at 1.5 and 0.25 times the first fundamental mode period.
Beam-column panel zones were modeled to account for their influence on the structural response, and P-delta effects were included to represent additional moments due to gravity loads. Soil-structure interaction was neglected by assuming fixed base conditions for the columns. The lumped plasticity model used for beams and columns, combined with Rayleigh damping based on NIST 17 specifications, ensured a comprehensive simulation of the structure's nonlinear behavior and vibrational modes.

2.4 Seismic Input and Ground Motion Selection

This study modeled the structure, located in Vancouver, Canada, to assess its seismic performance under combined gravitational and lateral forces. A target spectrum was created to accurately reflect the seismic characteristics of the area, as shown in Figure 3. Seven actual earthquake records were chosen and adjusted to align with the target spectrum (Figure 4, providing a realistic scenario for the nonlinear response history analysis. This method was intended to replicate the complex interactions of seismic forces, offering a comprehensive assessment of the structural response and valuable insights for enhancing the design of buildings in earthquake-prone regions.

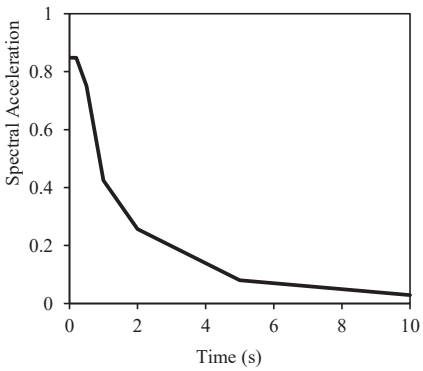
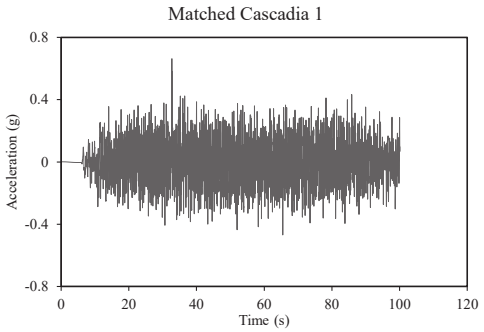


Figure 3. Seismic Target Response Spectrum.



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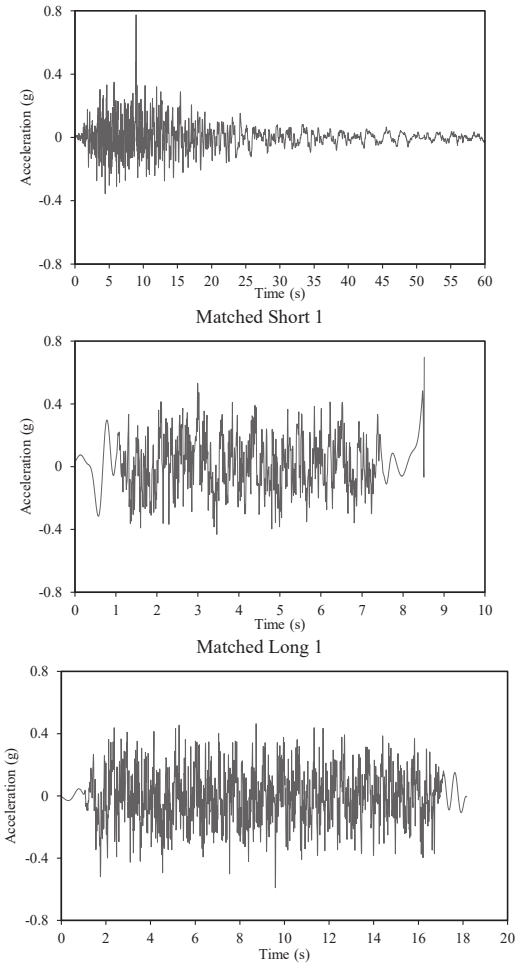

Figure 4. Time-History Seismic Input Function.

3 RESULTS AND DISCUSSIONS

The seismic behavior of the deficient RC frames strengthened with KBRBs was assessed using nonlinear dynamic analysis, and the findings show substantial enhancements in structural performance relative to the unretrofitted control frame. The results are presented in terms of story displacement, interstory drift ratio, story shear forces, and overturning moments, offering a comprehensive evaluation of the influence of the strengthening configurations.

Figure 5 illustrates the story displacement responses for the control frame and the three strengthened configurations: center bay (C), exterior bay (E), and combined center-exterior bay (EC). The results indicate that the control frame experienced excessive displacements at all story levels, with a maximum displacement of 69.85 mm at the tenth story. Conversely, all KBRB-retrofitted configurations significantly reduced the displacement, with the EC configuration showing the most effective response. The EC configuration significantly reduced maximum displacement at the top story, limiting it to 13.53 mm. The C and E configurations also improved, reducing top story displacements to 24.13 mm and 20.86 mm, respectively. This reduction in displacements underscores the effectiveness of KBRBs in enhancing lateral stiffness and mitigating excessive lateral movement, with the EC configuration delivering superior performance due to the synergistic placement of braces in both the center and exterior bays.

The interstory drift ratios for all configurations, as presented in Figure 6, further reinforce the observed improvements in structural performance. In the control frame, the drift ratios exceeded 0.2% at multiple story levels, peaking at 0.24% on the fifth story, indicating a high potential for structural damage under seismic loading. The retrofitted configurations substantially mitigated drift demands across all stories. The EC configuration again demonstrated the most effective reduction, with the peak drift ratio reduced to 0.04%. The C and E configurations

also significantly improved, achieving peak drift ratios of 0.08% and 0.07%, respectively. These results suggest that adding KBRBs effectively controlled lateral deformations and enhanced the deformation capacity of the deficient RC frames. The observed reductions align with the brace systems' improved stiffness and energy dissipation capabilities, particularly in the EC configuration, where dual placement provided balanced resistance.

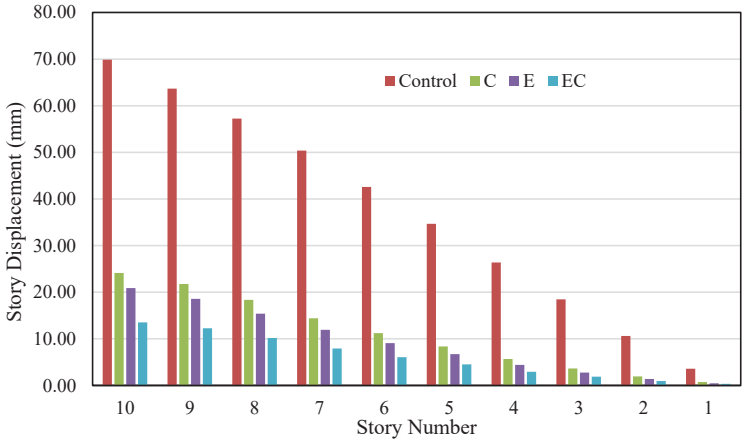

Figure 5. Story displacement response for the investigated structures

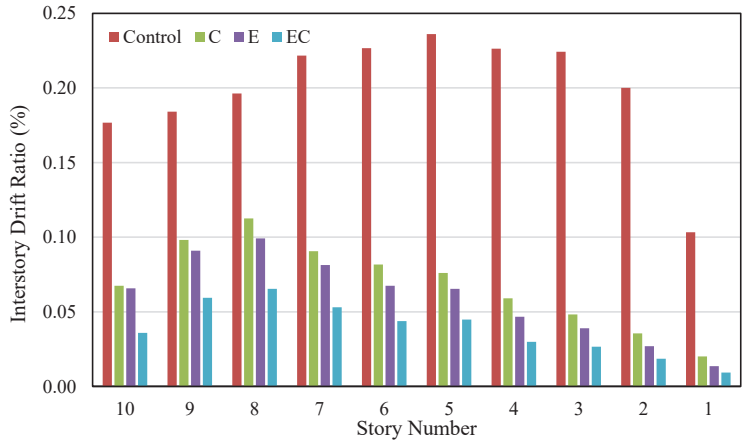

Figure 6. Interstory drift ratio response for the investigated structures

The story shear forces for the investigated configurations are presented in Figure 7. The control frame experienced lower story shear forces due to its inadequate stiffness and reduced resistance to lateral loads. However, introducing KBRBs significantly increased the shear forces across all stories, reflecting the enhanced lateral stiffness of the retrofitted structures. The EC configuration exhibited the highest story shear forces, reaching a maximum of 381.27 kN at the first story, compared to 347.54 kN for the control frame. The C and E configurations showed intermediate performance, with maximum shear forces of 360.72 kN and 370.78 kN, respectively. This increase in shear forces highlights the capacity of the retrofitted frames to effectively resist seismic loads, with the EC configuration again providing superior results due to its optimal brace placement, which evenly distributed the shear forces across the structure.

Figure 8 presents the story overturning moments for the control and retrofitted frames. The results reveal a consistent trend where the retrofitted configurations experienced higher overturning moments compared to the control frame. At the base level (first story), the EC configuration recorded the highest overturning moment of 8438.43 kN.m, followed by the E and C configurations with 8227.86 kN.m and 8027.52 kN.m, respectively. In comparison, the control frame exhibited a maximum base overturning moment of 7746.44 kN.m. This increase in overturning moments is attributed to the enhanced lateral stiffness and improved load-resisting capacity of the retrofitted frames. The EC configuration achieved the most uniform distribution of overturning moments across the stories, demonstrating its effectiveness in mitigating seismic effects while maintaining a stable response. The

results across all performance parameters demonstrate that KBRBs significantly enhance the seismic performance of deficient RC frames. The combined center-exterior bay configuration (EC) consistently outperformed the other scenarios, achieving the greatest reductions in story displacements and interstory drifts while effectively distributing shear forces and overturning moments. This superior performance can be attributed to the balanced and optimized placement of braces, which maximized energy dissipation and lateral resistance.

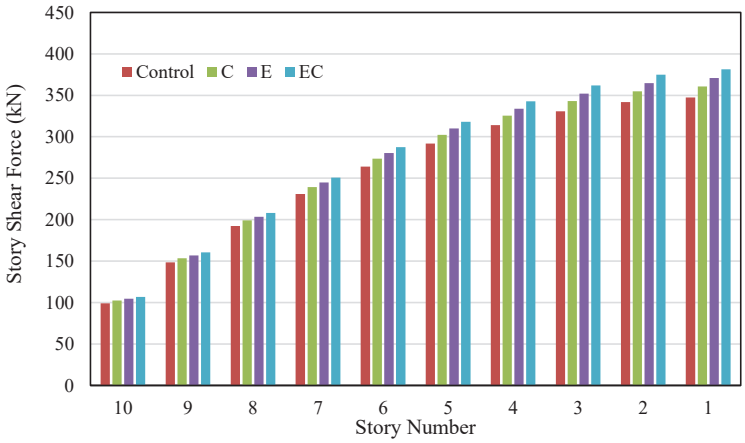

Figure 7. Story shear forces for the investigated structures

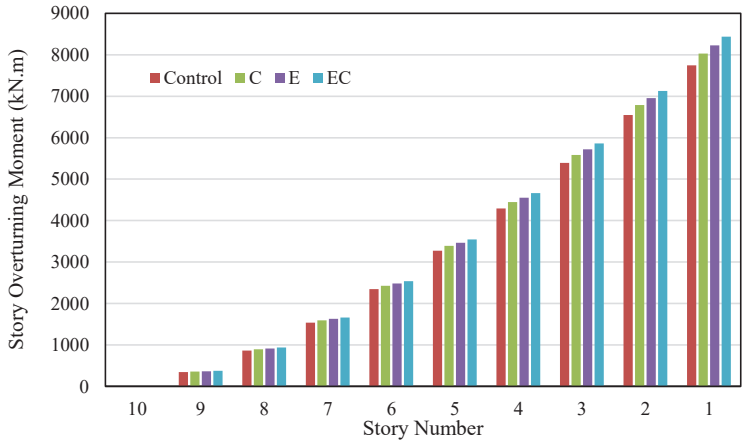

Figure 8. Story overturning moment for the investigated structures

4 CONCLUSION

Using detailed numerical simulations, this study evaluated the seismic behavior of deficient reinforced-concrete frames strengthened with knee-braced buckling-restrained braces (KBRBs). The results demonstrate the substantial potential of KBRBs to overcome the shortcomings of traditional retrofit methods and to enhance the seismic resilience of vulnerable RC systems. Key conclusions include:

1. The combined center-exterior bay configuration (EC) demonstrated superior performance by significantly reducing maximum story displacements by approximately 80% and peak interstory drift ratios by up to 83%, showcasing its effectiveness in enhancing lateral stiffness and deformation control.

2. The retrofitted frames exhibited improved distribution of story shear forces and overturning moments, with the EC configuration achieving the most uniform load-resisting response. This underscores the optimized placement of braces for balanced energy dissipation.

3. The integration of KBRBs effectively mitigated seismic demands, leveraging their non-buckling properties to enhance the energy dissipation capacity of deficient RC frames. This advancement addresses a critical gap in retrofitting solutions for aging infrastructure.

4. These findings contribute to the development of performance-based retrofitting strategies, offering actionable insights for engineers to adopt KBRBs in regions with high seismicity. The practical applications of this research are substantial, providing a methodological foundation for engineers and policymakers to implement these retrofitting strategies in real-world settings, thereby enhancing the resilience of aging infrastructures.

5. While the numerical analyses provide a robust foundation, the next steps include experimental validation to confirm these findings, optimizing KBRB designs for diverse seismic scenarios, and assessing their long-term performance and cost-effectiveness. Further investigation into the regional adaptability of KBRBs and their integration into existing building codes could also provide invaluable insights, ensuring broad applicability and adoption in seismic retrofitting practices.

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