

Buckling-Restrained Brace Arrangement in Regular RC Frames Based on Pushover Analysis

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Abstract: To improve the seismic performance of existing reinforced concrete (RC) frame structures with insufficient lateral resistance, this study investigates the influence of different buckling-restrained brace (BRB) arrangements on a typical five-story, 4×4 bay regular RC frame. Based on the original benchmark model, four retrofit schemes were developed by considering two brace forms, namely single diagonal and chevron braces, and two planar locations, namely mid-bay and end-bay arrangements. Five numerical models, including one unstrengthened structure and four BRB-retrofitted structures, were established in SAP2000 V26 for nonlinear static pushover analysis. Geometric and material nonlinearities were incorporated to simulate the inelastic behavior of beams, columns, and BRBs. Pushover analyses were conducted under uniform and inverted triangular lateral load distributions to evaluate the global seismic performance of the structure. The results indicate that all retrofit schemes significantly enhanced the base shear capacity and deformation capacity of the original frame. Under the uniform load pattern, the maximum base shear capacities of the four strengthened models increased by 295%, 148%, 145%, and 148%, respectively, relative to the original structure. Under the inverted triangular load pattern, the corresponding increases were 232%, 128%, 124%, and 127%, respectively. Among the investigated configurations, the mid-bay single diagonal brace arrangement achieved the most effective improvement in lateral resistance and was identified as the optimal retrofit scheme. These findings demonstrate that mid-bay BRB placement is more effective than end-bay placement for enhancing the seismic performance of regular RC frame structures.

Keywords: Reinforced concrete frame; Buckling-restrained brace; Seismic retrofit; Brace arrangement; Pushover analysis; Nonlinear static analysis

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1. Introduction

In recent years, earthquake activity has been frequent, and near-fault earthquakes are more destructive to buildings compared to far-field earthquakes. By studying the Parkfield and Pacoima earthquakes, Bolt first used the term “near-fault”^[1]. Liao studied the seismic response of reinforced concrete frame structures under near-fault earthquake motions in Jiji and compared it with the response under far-field earthquake motions^[2].

Mazzara and Vulkano examined the effectiveness of code provisions on the nonlinear dynamic response of reinforced concrete frame structures under near-fault earthquake motions [3]. Several past earthquakes, such as the 2001 Bhuj earthquake, the 2005 Kashmir earthquake, the 2006 Sikkim earthquake, the 2015 Nepal earthquake, and the 2023 Turkey earthquake, all resulted in partial or total collapse of RC buildings designed as MRF structures [4]. Therefore, BRB has been applied to the seismic reinforcement of steel frame structures and reinforced concrete (RC) frame structures [5-8].

2. Initial structural parameters

The building structure is a reinforced concrete frame structure, with a total of 5 stories and a total height of 16.5 m. Each story has a height of 3.3 m, and the plan dimensions are 16 m × 16 m (4 × 4 bays, with each bay 4 m). The seismic fortification intensity of the site is grade 8, and it is classified as a Class II construction site. Under rare earthquakes, $\alpha_{max} = 0.9$, and under frequent earthquakes, $\alpha_{max} = 0.16$. The site characteristic period $T_g = 0.35$ s. For the specific dimensions of the structural layout (Figure 1).

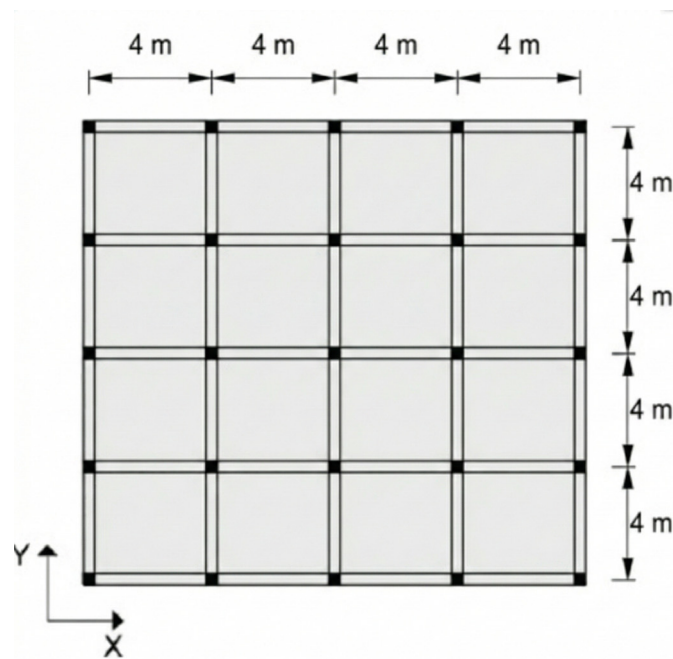


Figure 1. Structural plan layout.

3. Reinforcement configuration and model development

This study investigates the seismic retrofit of a typical five-story, four-by-four bay RC frame structure with inadequate seismic capacity. To improve the global seismic performance of the structure, buckling-restrained braces (BRBs) were installed along one side of the perimeter frame [9,10]. Based on the original structural model, four BRB arrangement schemes were developed by considering both the bracing form and the planar location of the braces. The bracing forms include a single diagonal brace and a chevron brace, while the planar locations include the mid-bay and end-bay positions of the perimeter frame. Accordingly, the following four strengthening schemes were designed (Figure 2).

- (1) Single diagonal brace, mid-bay arrangement;

- (2) Single diagonal brace, end-bay arrangement;
- (3) Chevron brace, mid-bay arrangement;
- (4) Chevron brace, end-bay arrangement.

In total, five structural models were established and analyzed in this study: one unstrengthened original benchmark model and four strengthened models with different BRB configurations.

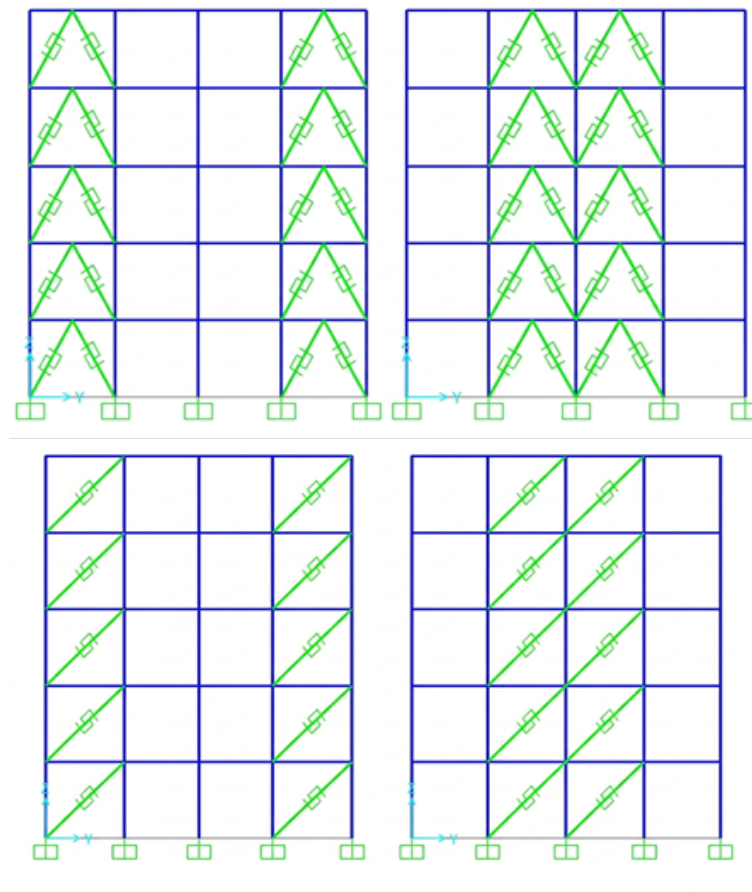


Figure 2. BRB reinforcement layout diagram

3.1. Strengthening scheme design and model establishment

This study focuses on a typical five-story, 4×4 bay reinforced concrete frame structure with insufficient seismic performance. To effectively enhance the overall seismic behavior of the structure, a strengthening strategy was proposed by adding buckling-restrained braces (BRBs) to one side of the exterior frame^[9,10]. Based on the unstrengthened benchmark model, four BRB configuration schemes were designed by considering the bracing type and its planar location. The two bracing types were a single diagonal brace and a chevron brace, and the two planar locations were the mid-bay and end-bay positions. Therefore, the following four retrofit schemes were developed:

- (1) Single diagonal brace at the mid-bay position;
- (2) Single diagonal brace at the end-bay position;
- (3) Chevron brace at the mid-bay position;
- (4) Chevron brace at the end-bay position.

Accordingly, five numerical models were established for comparative analysis, including one original unstrengthened model and four strengthened models with different BRB layouts.

3.2. Modeling

To evaluate the seismic performance of the structure, three-dimensional finite element models were developed using SAP2000 V26^[11] (**Figure 3**). Both geometric nonlinearity, including P-Delta effects and large-displacement effects, and material nonlinearity were taken into account^[11-13]. For the nonlinear simulation of beams and columns, the fiber plastic hinge approach (Fiber P-M2-M3 hinges) was adopted. The structural members were modeled as frame elements, with nonlinear fiber sections assigned at critical locations to capture local inelastic behavior^[11-13].

For the material constitutive laws, concrete behavior was represented using the Mander confined concrete model to account for the enhanced strength and ductility of core concrete under transverse reinforcement confinement^[14]. The peak compressive strain was set to 0.002, and the elastic modulus was taken as 23,500 MPa^[14]. Both longitudinal and transverse reinforcement bars were modeled using a nonlinear steel constitutive model with isotropic hardening. The elastic modulus was set to 200 GPa, and the post-yield hardening ratio was 0.005^[11,12].

For the BRB components, equivalent simulation was conducted using the nonlinear link element (Plastic Wen) in SAP2000^[13]. The BRB core was idealized with a rectangular cross-section of $150 \times 20 \text{ mm}^2$, and its axial hysteretic properties were assigned to reflect the stable energy dissipation capacity of the brace under cyclic tension and compression loading^[8,10].

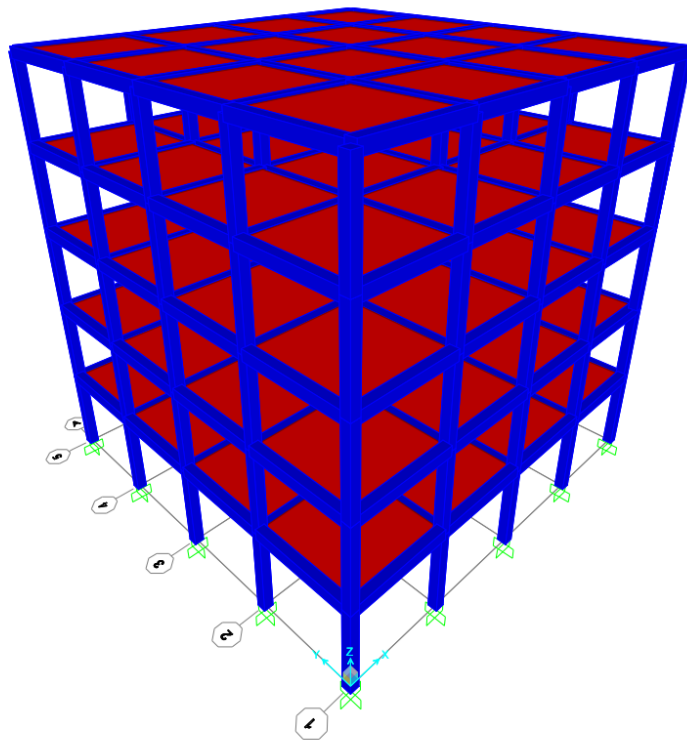


Figure 3. Three-dimensional structure.

4. Static elastic-plastic analysis (pushover analysis)

4.1. Analysis principles and parameter settings

Static elastic-plastic analysis, commonly referred to as pushover analysis, is an important nonlinear procedure for evaluating the seismic performance of structures and is widely used in both new building design and the assessment of existing structures [15–18]. The method establishes the nonlinear relationship between roof displacement and base shear, i.e., the capacity curve, thereby enabling systematic evaluation of the structural strength, stiffness degradation, and ductility characteristics [15–18].

In the analysis, lateral forces are incrementally applied to the structural model until the target displacement is reached. Owing to the symmetry and regularity of the five-story, 4×4 bay reinforced concrete (RC) frame structure considered in this study, seismic action was simulated only in the X direction. To comprehensively evaluate the lateral load-resisting performance of the structure, two horizontal load patterns were adopted in the pushover analysis: the uniform distribution pattern and the inverted triangular distribution pattern [15–18].

4.2. Comparison of load-bearing characteristics and configuration schemes

The base shear-roof displacement curves in the X direction for each model are shown in **Figures 4 and 5**. The results indicate that both the original structural model and the four BRB-retrofitted models were able to smoothly reach the prescribed target displacement of 0.33 m, which preliminarily confirms the effectiveness of buckling-restrained braces in improving the seismic performance of existing RC frame structures [15–20].

Based on the quantitative analysis of the pushover curves, the improvement in base shear capacity under the uniform load pattern is significant. Compared with the original structure, the maximum base shear capacities of the models with single diagonal braces at the mid-bay position, chevron braces at the end-bay position, chevron braces at the mid-bay position, and single diagonal braces at the end-bay position increased by 295%, 148%, 145%, and 148%, respectively [15–20].

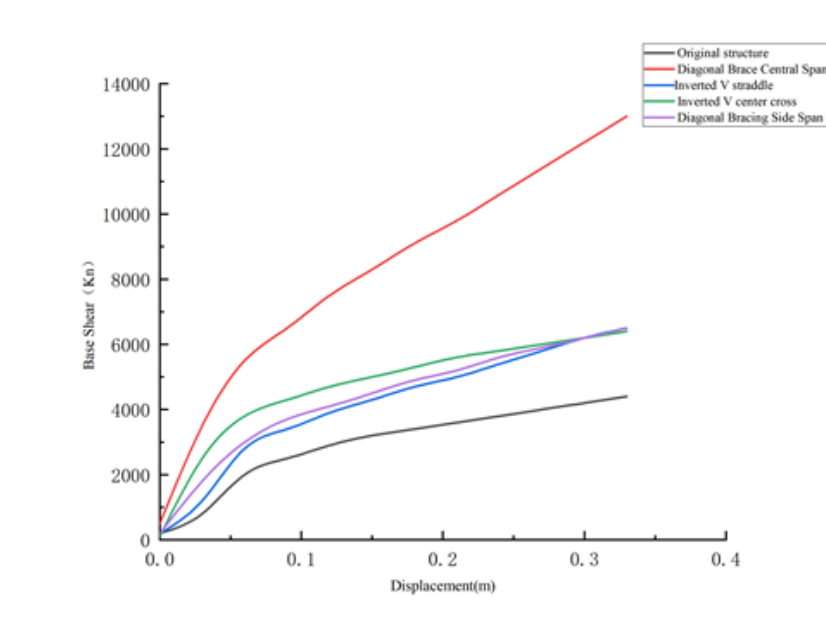


Figure 4. Push-over capacity curves of each model under uniform load

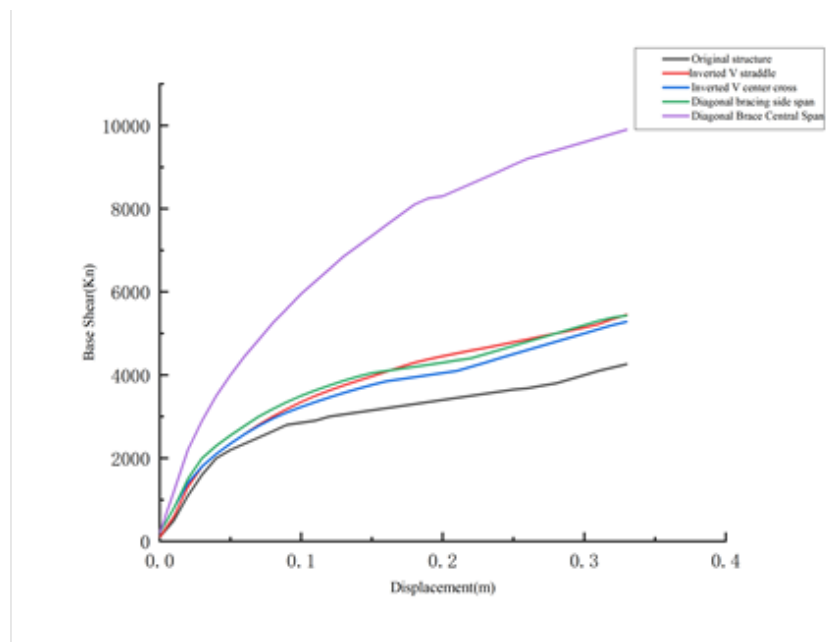


Figure 5. Overturning capacity curves of each model under inverted triangle load

Under the inverted triangular load pattern: the bearing capacity increase of the above four configuration schemes is 232%, 128%, 124%, and 127%, respectively.

The comparison results indicate that the BRB scheme with diagonal braces arranged at the central span most significantly enhances the base shear capacity of the original structure, making it the optimal reinforcement configuration within the scope of this study. In addition, the study found that placing braces at the central span can significantly improve the overall seismic performance of the structure.

5. Conclusion

Results have shown the effects of different horizontal load distribution patterns on structural response. The comparison indicates that the shear capacity of all models under uniform load is higher than that under the inverted triangular load pattern. Since the inverted triangular distribution simulates a more severe seismic effect (producing larger moments at the upper parts of the structure), it thus appears as a more critical load distribution pattern in seismic performance evaluation.

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Disclosure statement

The author declares no conflict of interest.

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