

# Investigation of Structural Behavior in Hybrid Reinforced Concrete Frames with Steel and GFRP Bars

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## ABSTRACT

The use of Fiber-Reinforced Polymer (FRP) bars as a solution for mitigating corrosion in reinforced concrete structures, including beams, slabs, bridges, and parking garages, has become increasingly widespread. However, concerns remain regarding the structural performance of FRP-reinforced members due to their linear-elastic behavior, brittle failure mode, and relatively low modulus of elasticity. Accordingly, this study presents a numerical investigation of ten one-story, one-bay reinforced concrete frames subjected to pushover analysis using ABAQUS software. The primary objective of this study is to evaluate and compare the performance of frames reinforced with different types of FRP bars in beams, columns, or both with that of steel-reinforced concrete frames. The results indicate that using CFRP bars in a one-story frame increases the maximum lateral load and the corresponding Drift ratio by approximately 63% and 32%, respectively, compared with the steel-reinforced frame. In contrast, the use of GFRP and AFRP bars in reinforced concrete frames reduces the maximum lateral load and the corresponding Drift ratio compared with the conventional reinforced concrete frame. The best structural performance in hybrid frames reinforced with GFRP and AFRP bars is achieved when these bars are placed in the beams rather than in the columns. In this case, the maximum lateral load increases by approximately 18% and 16% for GFRP and AFRP bars, respectively, compared with their use in the columns. Furthermore, the initiation and propagation of cracks in RC frames with different types of bars were investigated by comparing the maximum plastic strain at different drift levels.

## KEYWORDS

Hybrid RC Frames, Finite Element Method, FRP Bars, Drift, Cracking.

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## 1. Introduction

Durability issues in aggressive environments and the significant residual deformation of steel bars under seismic loading have increased interest in alternative reinforcing materials. To overcome these limitations, FRP bars has been proposed due to its corrosion resistance and high strength-to-weight ratio. However, since FRP-reinforced concrete members exhibit low ductility and limited energy dissipation due to their linear elastic behavior up to failure, this study investigates hybrid steel–FRP reinforced concrete structures to achieve the required strength and ductility.

Hybrid steel–FRP reinforced concrete moment-resisting frames and joints have been studied to optimize FRP replacement ratios, improve detailing in plastic hinge regions, and enhance seismic performance. Experimental and analytical studies on frames, sections, and beam–column joints indicate that hybrid reinforcement can reduce residual deformations while improving structural behavior and durability under lateral and cyclic loading conditions [1-4]. Experimental and analytical studies have investigated RC frames reinforced with steel and FRP (GFRP) under various configurations, including single-story and multi-story systems, focusing on nonlinear behavior, plastic hinge response, and lateral performance [5-7]. Genetic algorithms and neural networks have been applied to predict the effective moment of inertia in hybrid concrete beams using experimental data [8, 9]. In addition, the replacement of steel reinforcement with FRP bars in deep beams has been investigated, focusing on stiffness, cracking behavior, and overall structural response [10]. The behavior of RC columns reinforced with steel, FRP, and hybrid systems under cyclic, axial, and eccentric loading has been investigated experimentally and numerically [11, 12].

## 2. Methodology

A finite element model was developed in ABAQUS and validated against the experimental results of a GFRP-reinforced concrete frame reported by Hopartean et al. [13]. The validation was carried out by comparing the load– displacement response under a displacement-controlled pushover analysis. Subsequently, conventional RC and hybrid steel–FRP frames reinforced with different types of FRP bars were simulated and analyzed.

A reinforced concrete frame with overall dimensions of  $860 \times 1200$  mm was investigated, as shown in Figure 1. The longitudinal reinforcement in the beams and columns, together with the concrete compressive strength, is summarized in Table 1.

In this study, the Concrete Damage Plasticity (CDP) model was used. Concrete was modeled using C3D8R elements, while FRP reinforcement and stirrups were modeled using two-node linear beam elements (B31).

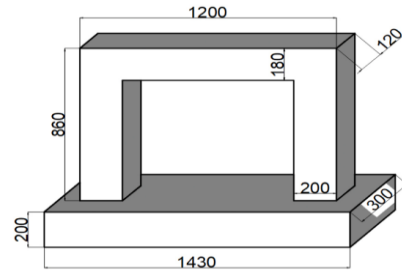


Figure 1. Geometry and dimensions of the frame (mm) [13]

Table 1. Frame details

Column reinforcement	Beam reinforcement	$f_{cu}$ (MPa)
8Ø6 mm GFRP	Top: 2Ø6 mm GFRP Bottom: 2Ø6 mm GFRP	42

In the numerical model, GFRP reinforcement was assigned a tensile strength of 1123 MPa and a modulus of elasticity of 47.8 GPa, while steel reinforcement was assigned 500 MPa and 200 GPa, respectively.

## 3. Results and Discussion

To compare the behavior of hybrid concrete frames, ten reinforced concrete frames with steel and various FRP reinforcements were modeled in ABAQUS. The frames were labeled using a four-letter naming system, where the first “C” denotes the column and “B” denotes the beam, while the second and fourth letters indicate the reinforcement type in the column and beam, respectively. “S” denotes steel, “G” denotes GFRP, “C” denotes CFRP, and “A” denotes AFRP bars. In the first stage, four RC frames reinforced with steel, GFRP, and hybrid bars were modeled, and their lateral load–drift response is presented in Figure 2.

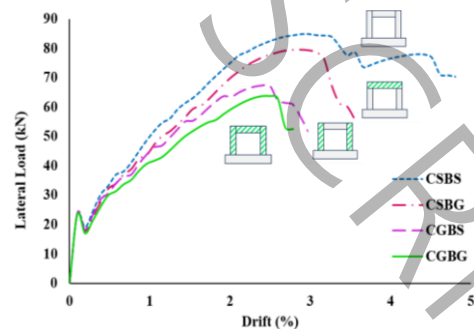
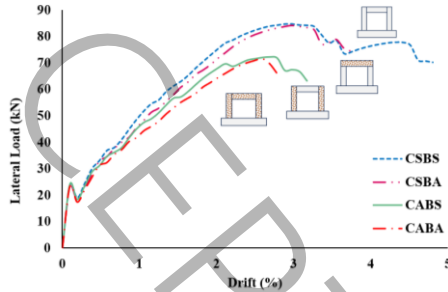
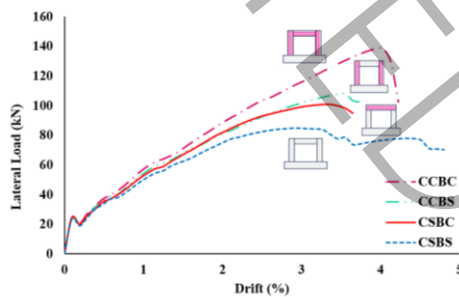


Figure 2. Comparison of lateral load–drift ratio response of RC frames reinforced with steel, GFRP, and hybrid bars

Figure 3 presents a comparison of the lateral load–drift response between the RC frame and the AFRP-reinforced and hybrid frames (CSBA and CABS). Figure 4 presents a comparison of the lateral load–drift response between the RC frame and the CFRP-reinforced and hybrid frames (CSBC and CCBS).



**Figure 3. Comparison of lateral load–drift ratio response of RC frames reinforced with steel, AFRP, and hybrid bars**



**Figure 4. Comparison of lateral load–drift ratio response of RC frames reinforced with steel, CFRP, and hybrid bars**

In the displacement-controlled pushover analysis, all frames exhibit nearly identical initial stiffness, indicating that the early elastic response is primarily controlled by the uncracked flexural stiffness of the concrete members, with negligible influence from the reinforcement type (steel or FRP). As the structure enters the nonlinear range and flexural cracking develops, the stress distribution across the cross-section changes, making the contribution of longitudinal reinforcement to flexural stiffness increasingly significant. Consequently, both the elastic modulus of the reinforcement and its placement within the structural members have a pronounced influence on the overall structural response. The use of GFRP and AFRP bars in beams reduces the post-cracking flexural stiffness because of their lower elastic modulus relative to steel, resulting in increased lateral drift. In contrast, the use of CFRP bars in columns enhances post-cracking flexural stiffness owing to their higher elastic modulus, thereby increasing the lateral stiffness and ultimate lateral load-carrying capacity of the structural system.

The cracking behavior of the different frames was evaluated based on the distribution of the maximum principal plastic strain (PE Max Principal). This

parameter was used to identify the critical regions susceptible to crack initiation and propagation and to compare the cracking patterns among the frames.

#### 4. Conclusions

The relationship between the maximum principal plastic strain and drift was investigated to evaluate crack development, demonstrating the usefulness of PE Max Principal for identifying critical damage regions and assessing structural performance under severe loading conditions.

Based on the lateral load–drift responses of the investigated hybrid frames, GFRP and AFRP bars are recommended for use in concrete beams. Replacing steel reinforcement with GFRP and AFRP bars reduced the drift at the maximum lateral load by approximately 19.46% and 13.09%, respectively. In contrast, CFRP bars increased the maximum lateral load capacity by approximately 20% and 27% when used in beams and columns, respectively, although they also increased the drift at the maximum lateral load by approximately 16.11%.

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