Numerical Investigation of the Seismic Behavior of RC Frames Strengthened at the Column-Base Region with HPFRCC Sheets Reinforced with GFRP Bars under Cyclic Loading

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ABSTRACT

The column-base region of reinforced concrete (RC) frames is highly vulnerable under cyclic seismic loading, where damage concentration and plastic hinge formation may cause rapid deterioration of lateral strength and energy dissipation. This study investigates a retrofit system based on precast high-performance fiber-reinforced cementitious composite (HPFRCC) sheets reinforced with glass fiber-reinforced polymer (GFRP) bars for improving the seismic response of RC frames. First, HPFRCC mixtures containing wollastonite were examined, and the mixture with 20% wollastonite replacement was selected as the optimum composition. Then, a finite element model of an experimentally tested RC frame was developed and validated against the measured cyclic response. After validation, the model was used for a nonlinear parametric study to evaluate the effects of HPFRCC sheet thickness, the number of GFRP bars, and bar diameter. The results showed that the proposed strengthening system significantly improved the lateral load-carrying capacity, stiffness retention, and energy absorption of the frame. The best retrofit configuration increased the lateral strength by about 36% and the energy dissipation capacity by about 40% relative to the reference specimen. The study also indicated that although thicker sheets and larger GFRP bars improved the absolute structural response, thinner sheets and smaller-diameter bars may provide higher strengthening efficiency in terms of material utilization. Overall, the proposed HPFRCC-GFRP system is a promising solution for seismic strengthening of RC frames, especially in the vulnerable column-base region.

KEYWORDS

HPFRCC, wollastonite, GFRP bars, RC frames, seismic strengthening.

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1. Introduction

The seismic performance of RC frames is strongly governed by the behavior of their critical regions under repeated lateral loading. Among these regions, the column-base zone is particularly sensitive because it is subjected to high bending moment demand, shear force, and crack opening and closing during earthquake excitation. Damage in this region often leads to stiffness degradation, strength loss, and undesirable failure mechanisms. Several strengthening strategies have been proposed for improving the performance of RC members, including FRP wrapping, steel jacketing, and cementitious overlays. However, some of these methods are associated with limitations such as debonding, brittle failure, corrosion sensitivity, or insufficient compatibility with the substrate. HPFRCC has attracted considerable attention because of its strain-hardening behavior, crack-control capability, and high toughness [1]. In addition, the incorporation of wollastonite can improve matrix density, reduce porosity, and enhance mechanical performance and durability [2,3].

Despite these advantages, limited research has examined the combined use of wollastonite-containing HPFRCC sheets and GFRP bars as a retrofit system for the column-base region of RC frames under cyclic loading. Previous studies have demonstrated the effectiveness of HPFRCC-based retrofitting in RC beams and frames [4,5], while FRP-based strengthening has also shown promising performance in concrete structures [6]. However, the combined influence of HPFRCC sheet thickness and GFRP bar geometry on the seismic response of RC frames has not been sufficiently addressed.

Accordingly, the main contribution of this study is the numerical evaluation of a precast HPFRCC-GFRP strengthening system for RC frames, together with material optimization using wollastonite and parametric assessment of the key retrofit variables. The geometric details of the strengthening system and the numerical configuration adopted for the strengthened RC frames are illustrated in Figure 1.

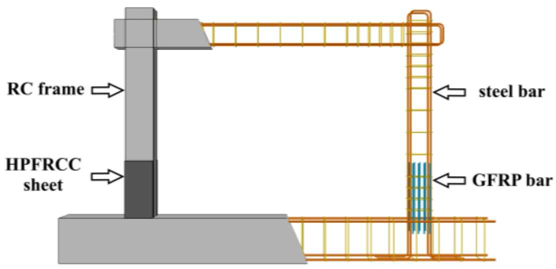

Figure 1. Details of the numerical model of the strengthened RC frames at the column-base region.

2. Methodology

The study was carried out in two stages. In the first stage, HPFRCC mixtures containing different amounts of wollastonite were experimentally examined. The matrix consisted of Portland cement, silica fume, silica sand, quartz powder, wollastonite powder, micro steel fibers, and PVA fibers. Based on the mechanical results, the mixture with 20% wollastonite replacement was selected as the optimum composition for the strengthening sheets [2,3].

In the second stage, a nonlinear finite element model of an experimentally tested RC frame was developed. The reference frame was modeled using suitable constitutive relations for concrete, steel reinforcement, and HPFRCC. The numerical model was first validated against the available experimental cyclic response, including the load-displacement hysteresis curves, cracking pattern, and stiffness degradation. After validation, HPFRCC sheets reinforced with GFRP bars were added to the column-base region.

The parametric analysis focused on three main variables: the thickness of the HPFRCC sheet, the number of GFRP bars, and the diameter of the GFRP bars. Cyclic lateral loading was applied through displacement-controlled analysis to reproduce seismic demand. The structural responses considered in the analysis included lateral load capacity, stiffness, crack propagation, energy dissipation, ductility, and strengthening efficiency index (SEI).

3. Results and Discussion

The finite element model reproduced the experimental cyclic response of the reference frame with satisfactory accuracy, confirming the reliability of the adopted modeling approach. The simulation captured the main characteristics of stiffness degradation, crack development, and hysteretic behavior under reversed loading.

The inclusion of wollastonite in the HPFRCC matrix had a beneficial effect on the composite properties. The mixture containing 20% wollastonite showed the best performance and was therefore selected for the strengthening sheets. This improvement can be attributed to the denser microstructure, lower porosity, and better crack-control capability provided by the wollastonite-modified HPFRCC [2,3].

Under cyclic loading, the strengthened frames exhibited a marked improvement in structural response compared with the unstrengthened reference frame. The retrofit system increased the lateral load-carrying capacity by approximately 36% and the energy absorption capacity by about 40%. Crack localization in the column-base region was better controlled, and the hysteretic response showed improved stability during repeated loading cycles. Similar improvements in RC members strengthened with HPFRCC-based systems have also been reported in previous studies [4,5].

Among the investigated configurations, larger sheet thicknesses and larger GFRP bar diameters generally improved the absolute structural response. However, the strengthening efficiency index indicated that thinner sheets and smaller-diameter bars may provide a more favorable balance between structural enhancement and material consumption. Therefore, the optimal retrofit design should not be selected solely on the basis of maximum strength, but also by considering efficiency and constructability.

Overall, the results confirm that the proposed HPFRCC-GFRP strengthening system is a promising seismic retrofitting solution for RC frames, especially in the vulnerable column-base region. The combined use of a strain-hardening cementitious matrix and GFRP reinforcement offers an effective way to enhance both strength and deformation capacity while maintaining a lightweight and practical retrofit solution [6]

4. Conclusions

This study numerically investigated the seismic behavior of RC frames strengthened at the column-base region using precast HPFRCC sheets reinforced with GFRP bars. The main conclusions are as follows:

- The HPFRCC mixture containing 20% wollastonite provided the best mechanical performance and was selected for the strengthening system.
- The developed finite element model successfully reproduced the cyclic response of the reference RC frame and was suitable for parametric analysis.
- The proposed strengthening scheme significantly improved the lateral load capacity and energy dissipation of the frame.
- The strengthening system increased the load-bearing capacity by about 36% and the energy absorption by about 40% relative to the unstrengthened frame.
- Increasing the sheet thickness and the size of GFRP bars generally improved the absolute structural response.
- From an efficiency viewpoint, thinner sheets and smaller-diameter bars may be more favorable when the objective is to maximize performance relative to the amount of retrofit material.
- The proposed approach provides a promising seismic strengthening strategy for RC frames, particularly for improving the performance of the critical column-base region.

5. References

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