# Flexural Strengthening of RC Beams Using Wollastonite-Containing High Performance Fiber Reinforced Cementitious Composite Sheets: Experimental and Numerical Investigation

**Reza Khaleghi***

Department of Civil Engineering, Ker.C., Islamic Azad University, Kermanshah, Iran

**ABSTRACT**

**Strengthening and rehabilitation of reinforced concrete (RC) beams are essential for extending service life and improving structural performance under increased loading demands, deterioration, and design deficiencies. Although externally bonded fiber-reinforced polymer (FRP) systems have been widely used for flexural strengthening, their application is often associated with brittle failure modes, bond-interface sensitivity, and durability concerns under severe environmental conditions. This study proposes an alternative strengthening system based on high-performance fiber-reinforced cementitious composite (HPFRCC) sheets containing wollastonite powder and reinforced with GFRP bars. The research consisted of material development, experimental characterization, and numerical investigation. Different wollastonite replacement ratios were considered to identify the optimum mixture. The mechanical behavior of the selected HPFRCC was then evaluated through tensile and flexural tests. A finite element model was developed in ABAQUS and validated against experimental results. After validation, a parametric study was conducted to assess the influence of sheet thickness and GFRP reinforcement arrangement on the flexural response of strengthened beams. The results showed that the mixture containing 20% wollastonite provided the best overall performance due to improved matrix densification and fiber-matrix interaction. The proposed strengthening system significantly enhanced both load-carrying capacity and energy absorption. The maximum load increased from 120.05 kN for the control beam to 267.41 kN for the strengthened specimen, while energy absorption increased from 1479.35 J to 2921.84 J. The numerical results also showed that increasing sheet thickness and reinforcement ratio generally improved structural performance, although the efficiency gain became less pronounced at higher reinforcement levels. The proposed system can therefore be considered a compatible and effective cement-based alternative for flexural strengthening of RC beams.**

**KEYWORDS**

**HPFRCC, Wollastonite powder, RC beams, Flexural strengthening, Finite element modeling.**

* Corresponding Author: Email: re.khaleghi@iau.ac.ir

## 1. Introduction

Reinforced concrete beams often require strengthening because of increased service loads, changes in structural use, aging, construction defects, or environmental deterioration [1]. In recent decades, FRP-based strengthening systems have been widely adopted as an efficient solution for upgrading RC beams because of their high strength-to-weight ratio and ease of installation [2]. However, the relatively brittle behavior of these materials, the sensitivity of adhesive bonding, and their reduced performance under severe temperature or moisture exposure have limited their long-term reliability. Consequently, the use of advanced cementitious composite materials has attracted increasing attention [3].

Among these materials, HPFRCC has emerged as a promising option because of its strain-hardening response, multiple microcracking behavior, and improved compatibility with concrete substrates [4]. Previous studies have demonstrated the potential of cement-based and fiber-reinforced composite laminates for strengthening RC members under flexural loading [5,6]. Nevertheless, limited research has addressed the structural application of wollastonite-containing HPFRCC sheets combined with GFRP bars as a hybrid strengthening system for RC beams.

Wollastonite, owing to its acicular microstructure and beneficial physicochemical interaction with cementitious matrices, can improve packing density, crack resistance, and fiber-bridging efficiency. The present study aims to develop an HPFRCC sheet containing wollastonite powder and to evaluate its effectiveness for flexural strengthening of RC beams through experimental and numerical investigations. The main contribution of this research is the introduction and assessment of a hybrid cement-based strengthening system that combines a wollastonite-modified HPFRCC matrix with GFRP bar reinforcement, together with a validated finite element framework for predicting its structural behavior.

## 2. Methodology

The study was carried out in three main stages: material design, experimental characterization, and numerical simulation. First, several HPFRCC mixtures were prepared using Type II Portland cement, silica fume, silica sand, quartz powder, superplasticizer, and hybrid fibers consisting of micro-steel fibers and PVA fibers. Wollastonite powder was introduced as a partial replacement for cement at different ratios to identify the optimum mixture.

The mechanical properties of the developed material were then evaluated experimentally. Direct tensile tests were performed on dog-bone specimens to assess tensile strength, strain-hardening behavior, and cracking response in accordance with JSCE recommendations [7]. Four-point bending tests were also conducted to examine the flexural behavior of the selected composite mixture. Based on the experimental results, the optimum mixture was adopted for the strengthening layer.

In the numerical phase, finite element models of the control and strengthened beams were developed in ABAQUS using the Concrete Damaged Plasticity model for concrete [8]. The constitutive relationships were defined using established stress-strain models for concrete in compression and tension [9,10]. After calibration and validation against the experimental response of the reference beam, the numerical model was employed for a parametric study. The investigated parameters included HPFRCC sheet thickness and the number and diameter of embedded GFRP bars.

## 3. Results and Discussion

The experimental investigation showed that incorporating wollastonite powder improved the microstructural quality and mechanical performance of the HPFRCC matrix, with the 20% replacement level providing the most favorable overall response. This mixture exhibited improved tensile behavior and crack distribution compared with the other mixtures, indicating more effective fiber-matrix interaction and improved internal stress transfer.

Figure 1 presents the proposed strengthening configuration, including the RC beam, the HPFRCC sheet, the embedded GFRP bars, and the loading arrangement. This figure is the most suitable choice for the extended abstract because it clearly illustrates the strengthening concept and test configuration in a compact format.

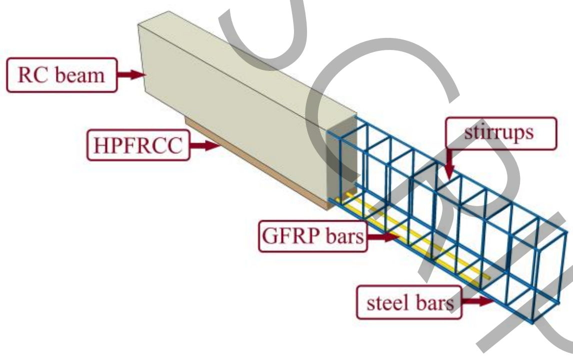


**Figure 1. Strengthened RC beam configuration with HPFRCC sheet and embedded GFRP bars**

The validated numerical model predicted the control beam behavior with good accuracy, with a peak-load error of about 2.8%, indicating acceptable agreement with the experimental results. The parametric study showed that the proposed strengthening technique significantly enhanced flexural performance; increasing sheet thickness improved stiffness, delayed crack propagation, and raised ultimate load, while increasing the diameter and number of GFRP bars improved load-carrying capacity and energy absorption, though with diminishing gains at higher reinforcement levels. Table 1 provides a concise summary of these key structural results and clearly demonstrates the overall effectiveness of the strengthening system.

**Table 1. Summary of key structural performance results**

| Specimen | Peak Load (kN) | Energy Absorption (J) |
|---|---|---|
| Control beam | 120.05 | 1479.35 |
| Strengthened beam | 267.41 | 2921.84 |

Compared with the control beam, the strengthened configuration increased the load-carrying capacity by more than 120% and nearly doubled the absorbed energy. These findings indicate that the proposed hybrid HPFRCC-GFRP strengthening layer provides not only higher strength but also improved deformability and post-cracking performance. From a practical point of view, the use of a cement-based strengthening layer may also offer better compatibility with the concrete substrate than conventional bonded FRP systems

## 4. Conclusions

Based on the experimental and numerical results, the following conclusions can be drawn:

- The HPFRCC mixture containing 20% wollastonite powder as a partial cement replacement exhibited the best overall mechanical performance among the investigated mixtures.

- The developed finite element model predicted the flexural response of the control and strengthened beams with acceptable accuracy, with a peak-load error of about 2.8% for the reference beam.

- The proposed HPFRCC-GFRP strengthening system significantly improved the structural behavior of RC beams, increasing the maximum load from 120.05 kN to 267.41 kN and the energy absorption from 1479.35 J to 2921.84 J.

- Increasing the thickness of the strengthening sheet and the amount of GFRP reinforcement generally improved beam performance; however, the efficiency of additional reinforcement decreased at higher reinforcement levels.

- The proposed cement-based hybrid strengthening technique can be considered a durable and compatible alternative to conventional FRP-based systems for the flexural rehabilitation of RC beams.

## 5. References


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