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# Experimental and Numerical Investigation of the Shear Performance of Continuous RC Beams Rehabilitated with BFRP and CFRP Materials

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**Abstract** Over the last few decades, the use of fiber-reinforced polymer (FRP) composites has emerged as one of the most effective and promising methods for strengthening and rehabilitating reinforced concrete (RC) structures, aiming to enhance their performance and extend their service life. Among the evolving innovations in the FRP family, BFRP stands out as a fresh and compelling solution, combining strength, durability, and affordability, ushering in a new era of efficient structural rehabilitation. In this work, seven continuous RC beams, each with an overall length of four meters, were loaded and then rehabilitated to improve the shear resistance using different types of BFRP and CFRP materials for comparison purposes. The same patterns of rehabilitation were applied to both FRP materials to facilitate comparison with the reference sample and assess the effectiveness of the rehabilitation. The experimental findings demonstrated a notable increase in shear strength due to FRP rehabilitation, with BFRP enhancements ranging from 34.4% to 77% and CFRP improvements varying between 16.4% and 98.7%. These results highlight the considerable load-bearing capacity provided by both materials, with BFRP emerging as a more economical option. The observed experimental behavior showed strong agreement with both Finite Element Modeling predictions and theoretical calculations, underscoring the effectiveness and reliability of FRP materials in the structural rehabilitation of RC beams.

**Keywords** Rehabilitation, CFRP, Shear Capacity, BFRP, Brittle Failure, Full-Scale Beams

## 1. Introduction and Background

Concrete remains one of the most extensively used construction materials due to its moldability, durability, and ability to achieve the desired mechanical strength, making it a preferred choice over other conventional building materials. Despite these advantages, concrete also presents notable limitations such as low tensile strength and limited strain capacity [1–4].

As the use of concrete expands rapidly, exceeding 7 billion cubic meters poured annually worldwide, the number of concrete structures in existence continues to grow at an unprecedented rate. Ensuring the long-term durability and serviceability of these structures necessitates significant repair and maintenance efforts. In many cases, repair or strengthening interventions are required within just a few years of construction, sometimes even immediately after completion. Over the last 30 years, the growing demand for repair and rehabilitation has fueled substantial progress in materials development, structural design approaches, construction practices, quality assurance and control systems, contracting models, and professional training. These improvements are essential for extending service life, reducing costs, and minimizing conflicts in the construction and maintenance of concrete infrastructure [5].

All RC components must be designed to effectively resist shear stresses to prevent such shear failure, since it is brittle and unpredictable, which leads to catastrophic conditions. In recent years, the structural engineering community has increasingly recognized the importance of addressing shear deficiencies in existing concrete structures. As a result, the development and implementation of reliable, cost-effective shear strengthening methods have become a major focus in rehabilitation efforts. Rather than opting for full replacement, which is often economically unfeasible and time-consuming, upgrading and reinforcing existing structures offers a practical solution. This approach not only extends the expected service life of infrastructure but also significantly reduces maintenance and repair costs. Given the growing global demand for infrastructure repair and reinforcement, investing in strengthening techniques has become a vital strategy. It ensures both structural safety and economic efficiency, while mitigating the broader impacts that large-scale replacements could impose on the economy [6–10].

Carbon fiber-reinforced polymer (CFRP) composites are now widely used to strengthen RC beams, particularly in flexural applications. This is due to their exceptional tensile strength, stiffness, and high elasticity. They also show excellent performance in resisting bending failure, while offering notable durability and fatigue resistance. The increased utilization of fiber-reinforced polymers (FRPs) in construction is largely due to their ability to withstand harsh environments and corrosion. CFRP remains a trusted choice for structural repair and upgrading [11–19].

FRP materials are lightweight, flexible, and durable, which makes them effective for improving the shear performance of RC elements. Numerous studies have emphasized the advantages of using FRPs in such applications, particularly for enhancing structural behavior under diverse loading situations. Recently, basalt fiber-reinforced polymer (BFRP) materials have been considered a viable alternative to conventional FRPs. These basalt fibers have gained attention because of their favorable mechanical attributes, including high tensile strength and outstanding environmental resistance [20]. Additionally, basalt fibers are eco-friendly and manufactured using sustainable processes, making them a green and economical option for retrofitting concrete elements [1,9,12,20–25]. Prior investigations have focused on the application of BFRP in maintaining structural performance and extending the lifespan of RC structures. Jiang et al. [26] studied the use of BFRP bars and jackets to recover the original strength of circular RC columns affected by seismic damage. Their findings showed that the flexural strength was significantly restored, along with improvements in both stiffness and displacement behavior.

In another study, experimental work was conducted to evaluate corrosion control in steel by replacing it with BFRP bars. Twelve full-scale RC beam samples were tested to assess torsional response. The results revealed that the strengthened beams exhibited better performance by reducing diagonal cracks through increased stirrup usage. The torsional strength and ductility of RC beams were significantly improved [16]. When the beam length was increased from 300 mm to 900 mm, a notable reduction in torsional capacity was observed, amounting to 52.32%. Although a greater stirrup ratio helped counteract the size effect, it could not entirely eliminate it [27]. Cui et al. [28] explored hybrid FRP systems combining near-surface mounted (NSM) BFRP bars with CFRP U-jacket end anchors. Their results indicated a 64% enhancement in load-bearing capacity when using these anchors, with significant improvements in beam ductility. The primary failure modes were related to concrete crushing and cover separation. Experimental and numerical studies supported the reliability of this strengthening method. Moreover, Aljidda et al. [29] examined how NSM BFRP reinforcement impacts the flexural performance of RC one-way slabs under four-point loading. They found it to be highly effective for slabs with lower steel reinforcement, achieving strength gains between 51% and 123% compared to unstrengthened slabs. Results confirmed that NSM BFRP bars significantly boost flexural strength, especially when the steel reinforcement is limited. In slabs with steel ratios of 0.48% and 0.95%, ductility increased by 10–53%, while flexural capacity rose between 29–79% and 21–44%, respectively. The study also concluded that the type of epoxy adhesive had a minimal effect on flexural behavior, with typical failure modes including steel yielding, concrete crushing, and BFRP rupture. Experimental results closely aligned with ACI 440.2R guidelines.

This study employs full-scale, two-span RC beams to closely replicate real-life structural conditions and gain a more precise understanding of material performance in shear rehabilitation applications. To restore the shear capacity of beams previously loaded to 70% of their ultimate shear capacity, lightweight as well as heavyweight BFRP sheets were implemented. Given the relatively limited research and application of BFRP compared to the more established CFRP systems, to allow for a direct comparison, this study also includes the use of CFRP sheets and laminates. Their incorporation provides a benchmark to evaluate the relative effectiveness of alternative strengthening materials and techniques. This approach highlights the novelty of evaluating BFRP's potential as a viable and efficient alternative for shear rehabilitation of RC elements.

# 2. Experimental Program

## 2.1. Concrete and Steel Bars

**Table 1** outlines the properties of the medium-strength ready-mix concrete used in beam casting. Concrete cubes were cast and tested per ASTM C192/C192M to determine the material's compressive strength. The average compressive strength measured was 32.4 MPa. Reinforcement included steel bars with a grade of 60 for the longitudinal direction, and stirrups made from grade 40 steel. Tensile tests revealed that the longitudinal steel bars had an average yield strength of 536.5 MPa

**Table 1.** Medium-strength concrete mix properties

| Type | Quantity (kg/m$^3$) |
|---|---|
| Silica Sand | 750 |
| Medium Aggregate | 590 |
| Fine Aggregate | 305 |
| Coarse Aggregate | 365 |
| Cement (OPC) | 205 |
| W/C | 0.79 |
| Superplasticizer | 35.7 |

## 2.2. FRP Materials

This study employed lightweight and heavyweight BFRP sheets to rehabilitate six full-scale continuous beams. Additionally, CFRP laminates and sheets were used in the rehabilitation process. **Figs. 1** and **2** illustrate the BFRP sheets, while **Figs. 3** and **4** depict the CFRP materials. **Tables 2** and **3** present the manufacturer-provided specifications for the BFRP and CFRP materials, respectively.

**Figure 1.** (10 cm width) heavyweight BFRP sheet

**Figure 2.** (60 cm width) lightweight BFRP sheet

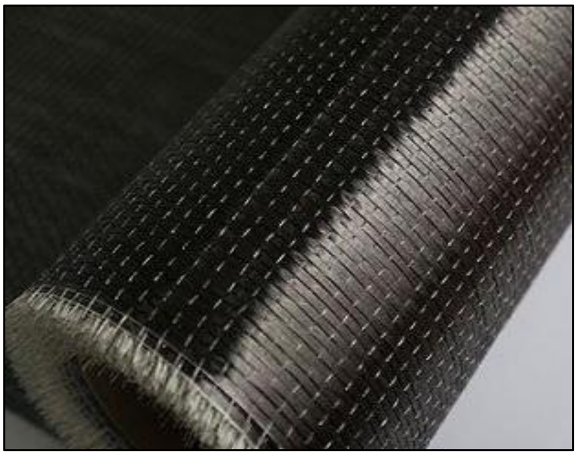


**Figure 3.** CFRP sheet

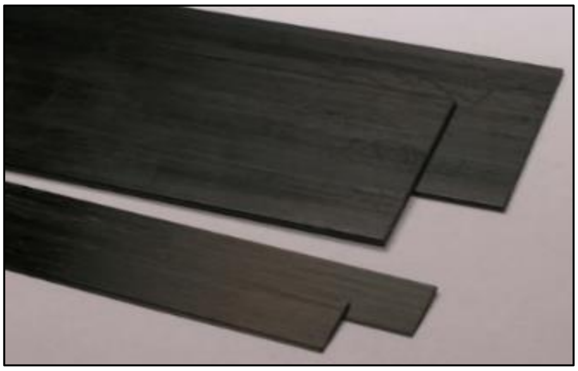


**Figure 4.** CFRP laminates

### 3.4. Comparative Evaluation of BFRP and CFRP Sheets as Rehabilitation Solutions

To assess the effectiveness of BFRP and CFRP sheets in rehabilitating RC samples with inadequate shear capacity, identical external bonding techniques were applied across all test specimens. The results indicated that both materials contributed significantly to improving shear resistance. However, heavy BFRP sheets provided better structural performance under load, especially when applied at 90 ° and 45 °orientations, outperforming CFRP in certain cases. This behavior is attributed to the lower stiffness of basalt fibers, which makes their strengthening efficiency highly dependent on fiber orientation; fibers oriented at 90 °were more effective in directly intercepting dominant shear cracks. While CFRP possesses superior tensile strength and mechanical advantages, the broader surface coverage of BFRP sheets helped counterbalance its lower strength, leading to enhanced load capacity. The measured increases in shear strength for BFRP-treated samples ranged from 34.4% to 77% compared to the untreated reference specimen.

**Table 6.** Experimental, numerical, and code-based results

| Groups | Samples | Maximum Exp ultimate load (kN) | Ultimate Exp deflection (mm) | Maximum FE ultimate load (kN) | Ultimate FE deflection (mm) | $P_{Theo}$ (kN) | Change percentage in shear strength (%) |
|---|---|---|---|---|---|---|---|
| Group A | CL | 143.1 | 5.76 | 136 | 3.22 | 130 | - |
| Group B | B90 | 253.36 | 7.14 | 225.4 | 6.06 | 224.5 | 77% |
|  | B45 | 192.26 | 3.22 | 187.86 | 2.44 | 191.4 | 34.4% |
|  | BF | 218.7 | 3.84 | 209.5 | 3.2 | 196.8 | 52.8% |
| Group C | C90 | 191.1 | 3.68 | 184.6 | 2.96 | 170.5 | 33.5% |
|  | C45 | 164 | 4.1 | 142.8 | 3.33 | 154.7 | 16.4% |
|  | CF | 284.3 | 9.7 | 277.8 | 6.9 | 258.3 | 98.7% |

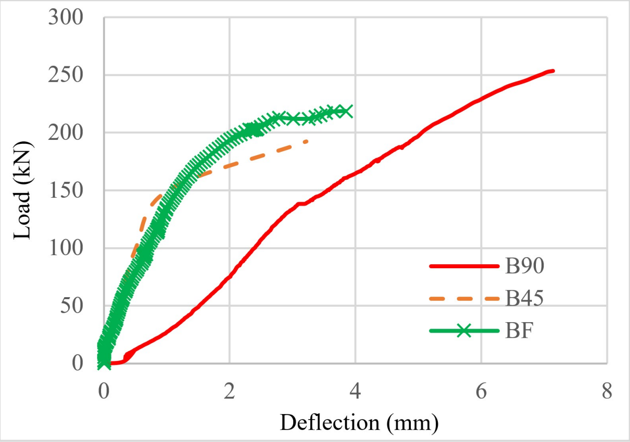
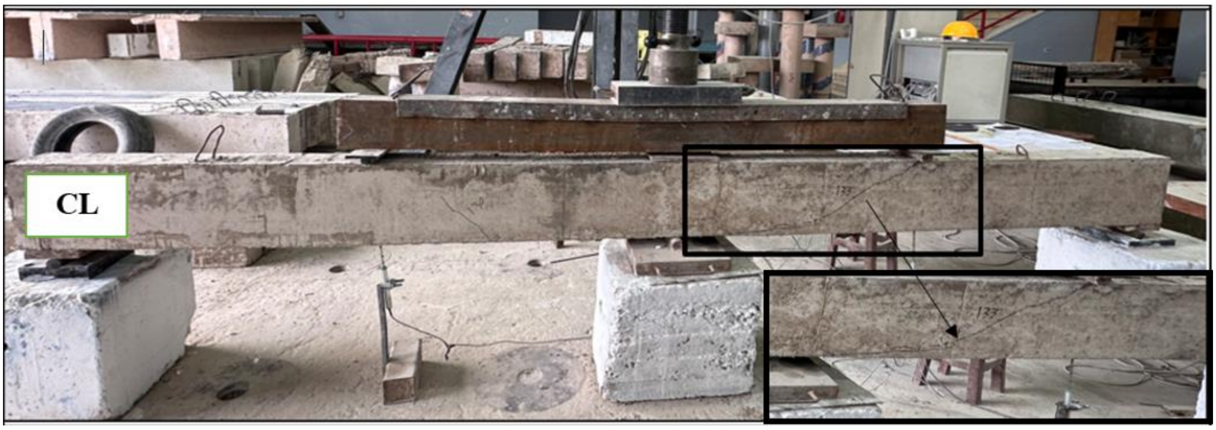


**Figure 11.** Load deflection curves for Group B

**Figure 12.** Load deflection curves for Group C



**(a)**

**(b)**

**(c)**

**(d)**

**(e)**

(f)

(g)

**Figure 13.** Crack patterns

On the other hand, specimens retrofitted with fully wrapped CFRP sheets showed even greater enhancements in shear strength than those reinforced with lightweight BFRP. Unlike BFRP, the higher tensile strength and elastic modulus of CFRP enable full wrapping, providing more effective confinement and stress redistribution along the beam, which results in the highest maximum load capacity. This highlights the higher effectiveness of CFRP, attributed to its excellent tensile behavior and stiffness, which allow it to better resist shear-related damage, especially in critical regions of the beam.

Despite the advantages of CFRP, both lightweight and heavyweight BFRP, along with CFRP, proved beneficial in restoring the performance of full-scale RC beams. It should be noted that the relatively lower performance of fully wrapped BFRP specimens compared to the 90° configuration is related to stress utilization efficiency rather than a negative confinement effect. Among them, BFRP stands out as the more cost-effective option, making it a practical choice for structural upgrades when working within financial limitations.

## 4. Numerical Findings

The structural response of continuous RC beams rehabilitated with basalt and carbon materials was numerically examined through advanced 3D nonlinear finite element analysis. The numerical model was developed with the objective of reproducing the global structural response, failure mode, and comparative strengthening efficiency rather than achieving exact stiffness matching at early loading stages.

### 4.1. Geometrical Characteristics and Element Identification

Table 7 summarizes the geometric specifications, material configurations, and element types used in the finite element modeling of continuous RC beams in ABAQUS.

### 4.2. Mesh Model Type and Specification

To ensure accurate representation of all components, different element types were utilized in the modeling process. The concrete beam, as well as the support and loading plates, were meshed using solid elements (C3D8R), while the steel reinforcement bars were modeled with 3D truss elements (T3D2). The CFRP and BFRP strengthening materials were represented using shell elements (S4R). A structured mesh with a global element size of 50 mm was implemented to enhance the visualization of crack patterns and improve the precision of deflection predictions. This mesh size was selected to balance computational efficiency with solution accuracy. As illustrated in **Fig. 14**, the beam geometry was discretized using hexagonal mesh elements with a uniform size of 50 mm.

### 4.3. Boundary Conditions and Loading

To replicate realistic boundary conditions, supports such as rollers and pins were implemented using appropriate constraint techniques. A displacement-controlled loading method was used, gradually increasing in a linear pattern to avoid complications typically observed with load-controlled methods. Most component interactions were modeled through tie constraints. The connection between concrete and steel reinforcement was represented using an embedded region approach, assuming perfect bond with no slip.

To enhance computational efficiency at the beginning of the analysis, the duration of the initial step was limited to 1 second. A pre-loading stage was added to simulate the beam rehabilitation process and align the model with the actual experimental setup. This step was critical to establish accurate initial conditions. The pre-load was applied over a very short duration of $1 \times 10^{-10}$ seconds, effectively reducing computational time while maintaining simulation accuracy.

A perfect bond between concrete and steel reinforcement was assumed using the embedded region technique, neglecting potential bond slip effects. Additionally, supports and loading plates were idealized, which may lead to a stiffer numerical response compared to experimental results, particularly at low load levels.

**Table 7.** Model components and definition

| Component | Details |
|---|---|
| Beam Dimensions | Width: 150 mm; Height: 300 mm; Span Length: 4000 mm |
| Rehabilitation Materials | BFRP sheets (various densities), CFRP sheets, and laminates |
| Reinforcement Type | Embedded steel bars |
| Loading and Support Plates | Modeled to replicate experimental conditions |
| Concrete Element Type | 3D solid elements |
| Steel Reinforcement Element | Wire elements |
| BFRP/CFRP Element Type | Shell elements used for both sheets and laminates |
| Support & Loading Plates | Modeled using solid elements |
| Modeling Approach | Each part was created individually in the ABAQUS Parts Module |
| Purpose of Part Separation | To allow detailed control over geometry and interaction definitions during simulation stages |

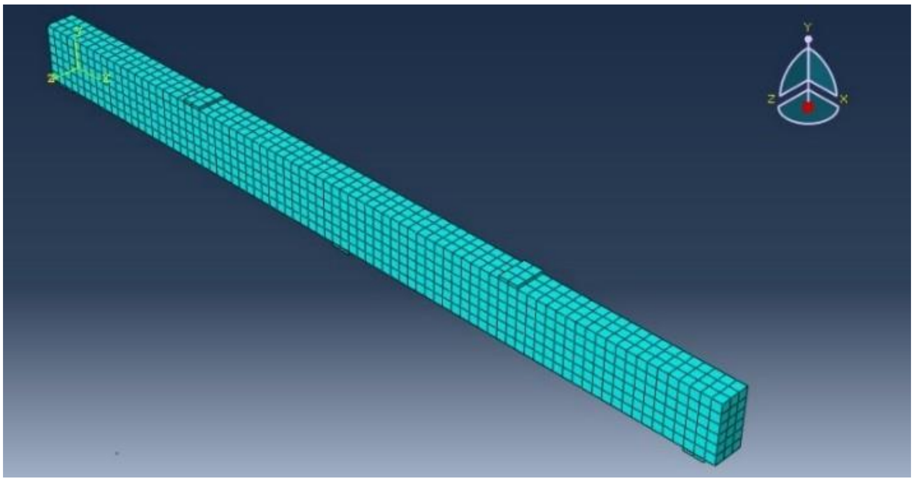


**Figure 14.** Concrete mesh

**Table 8.** Materials properties

| Material | Property | Value | Notes |
|---|---|---|---|
| Concrete | Compressive strength | 32.4 MPa | Medium-strength concrete |
| | Elastic modulus | 24,421.92 MPa | |
| | Poisson’s ratio | 0.2 | |
| Concrete Damage Parameter (CDP) | Tension damage parameter (dt) | 0 to 1 (0 = no damage, 1 = total loss) | Represents stiffness and strength reduction due to tensile cracking |
| | Compression damage parameter (dc) | 0 to 1 (0 = no damage, 1 = total loss) | Represents stiffness and strength reduction due to compressive crushing |
| Steel Bars | Yield strength | 536.5 MPa | Modeled as linear elastic-perfectly plastic |
| | Elastic modulus | 200 GPa | |
| | Density | $7.8 \times 10^{-9}$ kg/mm³ | |
| | Poisson’s ratio | 0.3 | |
| BFRP & CFRP | Behavior | Linear elastic up to failure | Full bond interaction with concrete via tie constraints |
| | Properties | Refer to Tables 3 and 4 | Includes lightweight and heavyweight BFRP sheets, CFRP sheets, and laminates |

## 4.4. Material Properties

**Table 8** summarizes the material properties applied in the numerical simulation of RC beams.

## 4.5. Load-Deflection Behavior

**Fig. 15** illustrates the load-displacement responses, demonstrating a notable agreement between the results of the finite element simulations and the experimental findings. **Table 6** presents a comparison of the ultimate load capacities, showing variations that range from 2.2% to 12.9%.

The differences in maximum deflection were more substantial, with deviations between 15.1% and 44%. These discrepancies are influenced by the simplified boundary conditions applied in the numerical model, which may not accurately reflect the real experimental setup. The higher initial stiffness observed in the numerical response of the control specimen (CL) is mainly attributed to idealized boundary conditions, absence of initial microcracking, and perfect material continuity assumed in the finite element model. These simplifications are commonly adopted in nonlinear FE simulations and primarily affect the early elastic response, while having a limited influence on the ultimate load capacity and failure mechanism.

Such simplifications can affect the precision of simulated load responses and beam deflection patterns. Moreover, some degree of inaccuracy can also arise from the use of theoretical models that assume linearity and do not fully capture the intricate behavior of structural elements when subjected to loading.

## 4.6. Crack Patterns and Failure Mode

**Fig. 16** presents the observed cracking behavior and failure mechanisms in the analyzed beams. Tensile stress was visualized using a color gradient, red indicating areas of high stress, yellow showing moderate stress, and blue representing low stress. The finite element results showed that failure was primarily governed by shear, with diagonal cracks forming from the loading points and progressing toward intermediate support. These regions, especially in continuous beams, experienced the highest shear forces. The presence of these diagonal cracks, which are characteristic of brittle shear failure, highlights the concentration of tensile stresses in critical areas. The simulation results closely matched the experimental data, effectively capturing both the crack propagation and the failure zones, thereby validating the model’s accuracy in reproducing the actual structural behavior of RC beams under shear loading.

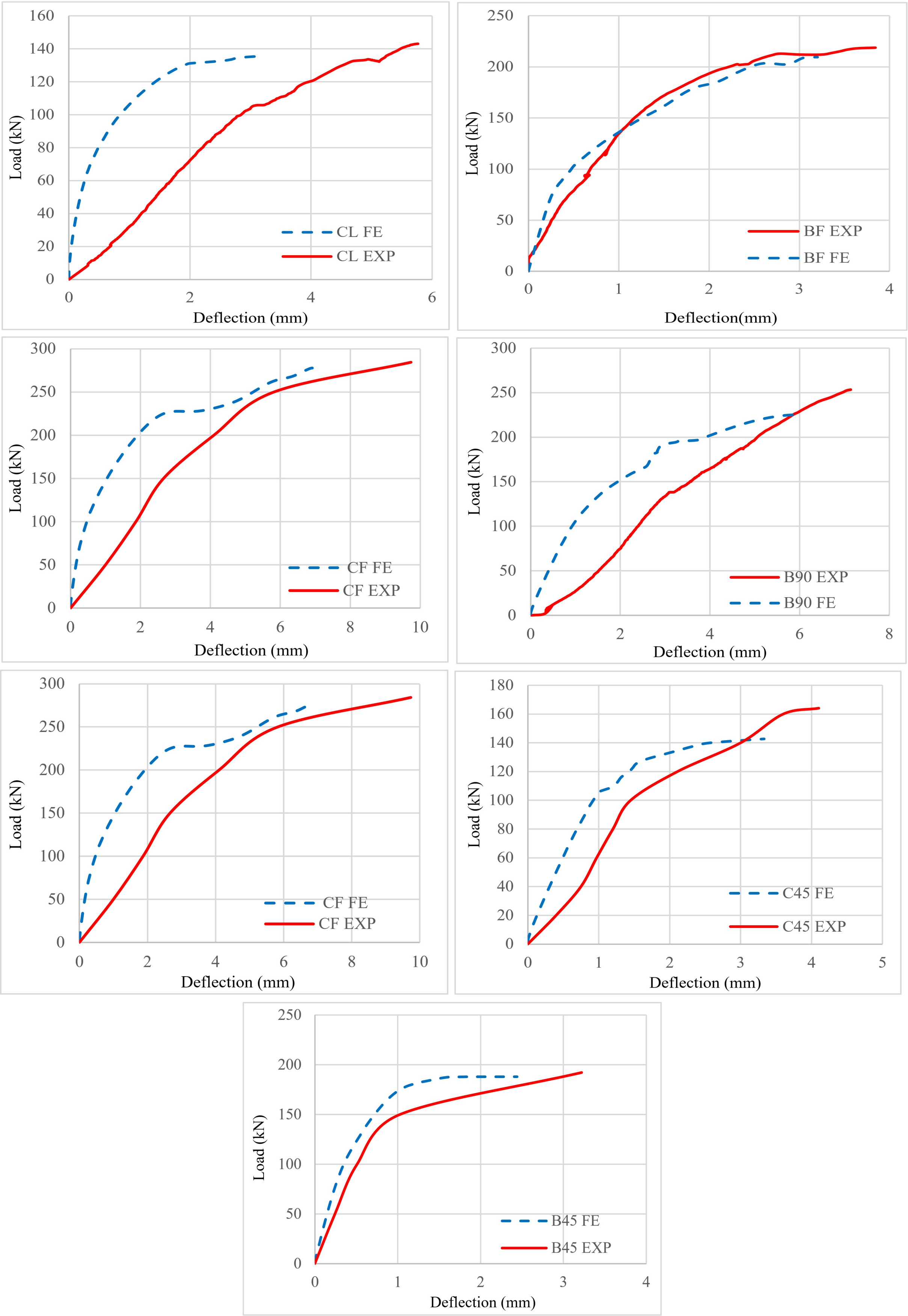
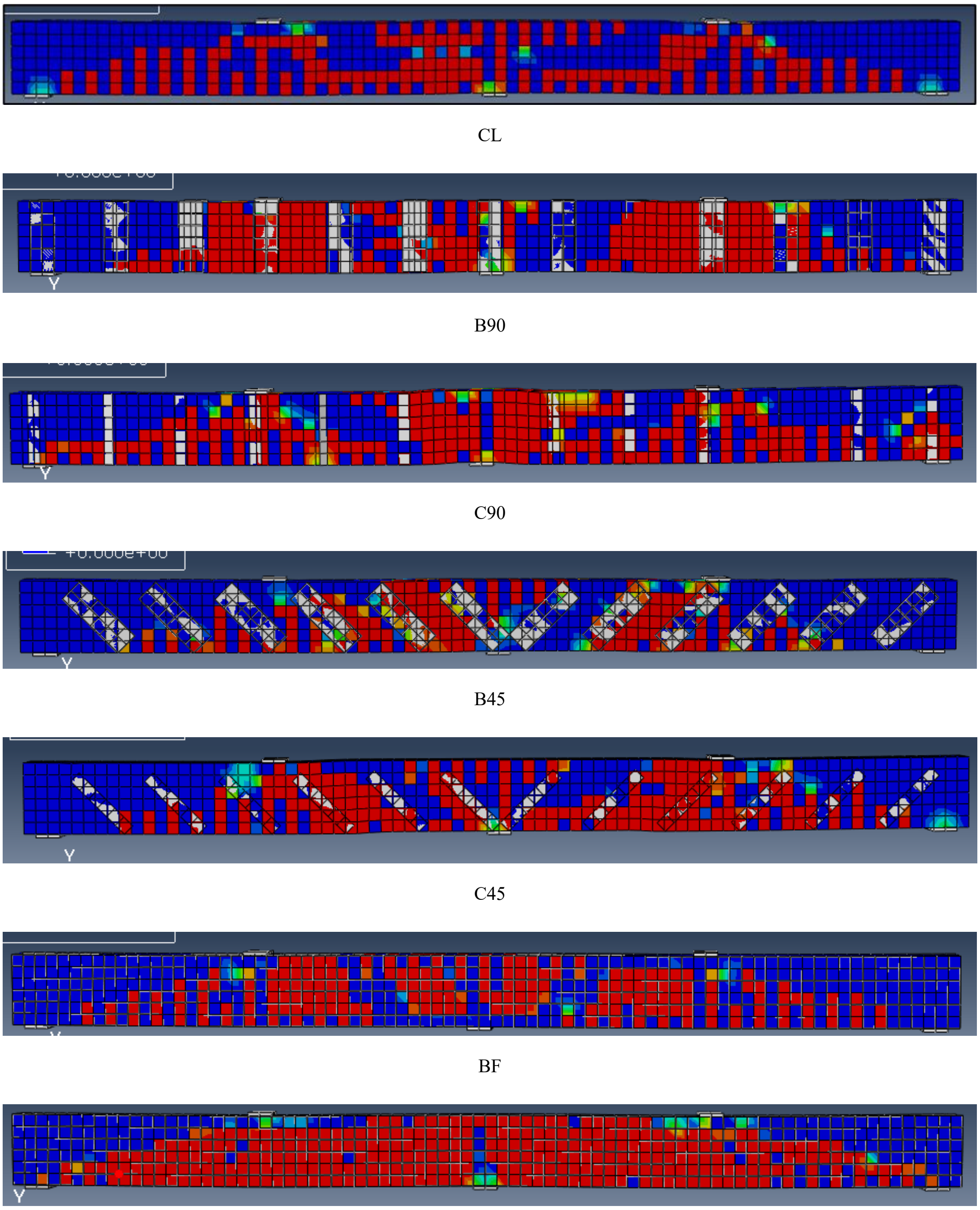


**Figure 15.** Experimental and numerical load-deflection curves



CL

B90

C90

B45

C45

BF

CF

**Figure 16.** Numerical failure mode

## 5. Theoretical Investigation

To assess the theoretical performance, the guidelines from ACI 440.2R-08 [31] were applied to evaluate the shear strength of the tested RC beams strengthened with BFRP and CFRP. For the analytical evaluation, key input parameters such as the cube compressive strength of concrete and the average yield strength of reinforcing steel (measured through standard material testing) were incorporated into the model.

**Table 5** provides a comparison of the theoretical shear strength values derived from different modeling approaches. The results demonstrated differences ranging from 0.46% to 11.37%, which indicates a good correlation between experimental outcomes and theoretical predictions as shown in **Fig. 17**. This reinforces the consistency of the analysis methods and supports the validity of using such design approaches for FRP-strengthened RC elements. **Fig. 18** presents the step-by-step procedure used in calculating the predicted load values.

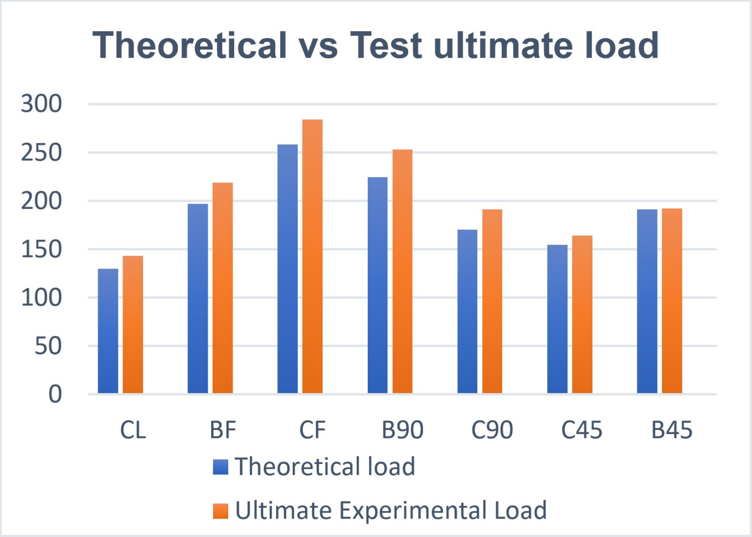
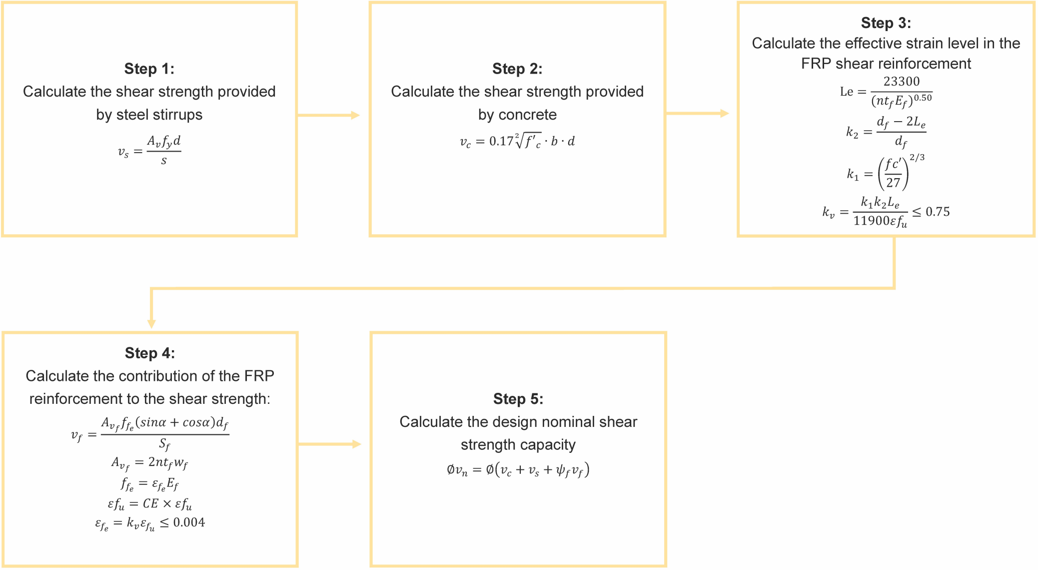


**Figure 17.** Experimental and theoretical load capacity for beam samples



**Step 1:**
Calculate the shear strength provided by steel stirrups
$$v_s = \frac{A_v f_y d}{s}$$

**Step 2:**
Calculate the shear strength provided by concrete
$$v_c = 0.17\sqrt[2]{f'_c} \cdot b \cdot d$$

**Step 3:**
Calculate the effective strain level in the FRP shear reinforcement
$$\mathrm{Le} = \frac{23300}{(nt_f E_f)^{0.50}}$$
$$k_2 = \frac{d_f - 2L_e}{d_f}$$
$$k_1 = \left(\frac{fc'}{27}\right)^{2/3}$$
$$k_v = \frac{k_1 k_2 L_e}{11900\varepsilon f_u} \leq 0.75$$

**Step 4:**
Calculate the contribution of the FRP reinforcement to the shear strength:
$$v_f = \frac{A_{v_f} f_{f_e}(sin\alpha + cos\alpha)d_f}{S_f}$$
$$A_{v_f} = 2nt_f w_f$$
$$f_{f_e} = \varepsilon_{f_e} E_f$$
$$\varepsilon f_u = CE \times \varepsilon f_u$$
$$\varepsilon_{f_e} = k_v \varepsilon_{f_u} \leq 0.004$$

**Step 5:**
Calculate the design nominal shear strength capacity
$$\emptyset v_n = \emptyset(v_c + v_s + \psi_f v_f)$$

**Figure 18.** Procedure used in the calculation of the predicted load values

# 6. Conclusions

Based on a comprehensive comparison of experimental observations, numerical simulations, and analytical methods, the following key conclusions were drawn:

1. Strengthening RC beams with both lightweight and heavyweight BFRP sheets arranged in varying configurations significantly enhanced their shear performance, with improvements ranging from 34.4% to 77%. Similarly, the application of CFRP sheets and laminates contributed to increased shear resistance, with gains between 16.4% and 98.7% when compared to unstrengthened beams. These results indicate the effectiveness of FRP-based rehabilitation systems under the tested configurations.
2. The effectiveness of FRP strengthening was found to depend on both fiber type and configuration. For BFRP-strengthened beams, fibers oriented at 90° provided the highest load-carrying capacity, highlighting the importance of fiber alignment with dominant shear cracks. In contrast, CFRP-strengthened beams achieved their highest capacity when fully wrapped, benefiting from the superior tensile strength and stiffness of carbon fibers.
3. While CFRP generally exhibited higher strengthening efficiency, heavyweight BFRP sheets demonstrated competitive performance in certain configurations. Considering their lower material cost, BFRP sheets represent a practical and economical alternative for shear strengthening applications where moderate performance enhancement is sufficient.
4. The numerical finite element models captured the overall structural response, failure modes, and crack propagation trends observed experimentally.

Although discrepancies were noted in initial stiffness—primarily due to idealized modeling assumptions—the numerical results showed good agreement with experimental ultimate loads, supporting their use for comparative and parametric analyses.

5. Analytical predictions based on ACI 440.2R-08 design provisions showed reasonable agreement with experimental results, with safety margins ranging from 0.46% to 11.37%. This confirms the applicability of the design guidelines for estimating the shear capacity of FRP-strengthened RC beams within the limitations of the present study.

## 7. Limitations and Future Research

The findings presented in this study are subject to certain limitations that should be acknowledged. The experimental program was conducted using one specimen per strengthening configuration, which restricts the ability to draw statistically generalized conclusions, particularly considering the inherent variability of concrete materials and construction practices. Therefore, the results should be interpreted as indicative trends reflecting the relative performance of the strengthening schemes investigated rather than definitive design recommendations.

Future research should focus on expanding the experimental database by testing a larger number of specimens for each configuration to improve statistical reliability. Additionally, further studies could investigate the influence of other parameters, such as different concrete strength classes, fiber anchorage systems, long-term durability effects, and cyclic or fatigue loading conditions. Such investigations would contribute to a more comprehensive understanding of the shear behavior of FRP-strengthened RC beams and support the development of more robust design guidelines.

## Declaration of Competing Interest

The authors declare no conflicts of interest.

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