

Structural Strength Performance of Carbon Fiber Reinforced Polymer on High-Strength Concrete Beams-A Review

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Abstract—Carbon Fiber Reinforced Polymer (CFRP) is widely employed to strengthen reinforced concrete (RC) beams due to its high strength-to-weight ratio, corrosion resistance, and ease of application. The use of CFRP on **high-strength concrete (HSC)** beams, however, involves unique challenges arising from HSC's high stiffness and brittle failure behaviour. This review synthesizes experimental, analytical, and numerical studies on CFRP-strengthened HSC beams. Key areas covered include flexural and shear strengthening, bond behaviour, failure mechanisms, analytical/numerical modeling, design practices, and durability. The review also highlights research gaps and proposes future directions to improve design and application of CFRP in HSC beam strengthening.

Index Terms—CFRP, high-strength concrete, RC beam strengthening, flexure, shear, bond behaviour, failure mode, durability.

I. INTRODUCTION

Reinforced concrete (RC) structures often require strengthening due to aging, increased load demands, or environmental deterioration. Rehabilitating such structures using external reinforcement is frequently more economical than full replacement.

Carbon Fiber Reinforced Polymer (CFRP) is a preferred material for strengthening because it offers high tensile strength, low weight, and resistance to corrosion. However, when applied to **high-strength concrete (HSC)**, the behaviour of the strengthened member can differ significantly from that of normal-

strength concrete systems. HSC typically exhibits higher compressive strength and modulus, but also more brittle failure and different crack propagation characteristics.

Given these distinctions, it becomes essential to understand how CFRP interacts with HSC beams—in terms of bond, failure, and performance under loading. This paper reviews the current state of knowledge, with a focus on experimental findings, analytical and numerical models, bond mechanics, failure modes, durability, and design considerations, with special attention to HSC contexts.

II. MATERIAL PROPERTIES AND BOND BEHAVIOR

A. CFRP Properties

CFRP composites comprise high-strength carbon fibers embedded in a polymer (commonly epoxy) matrix. Their mechanical behaviour depends on fiber orientation, fiber volume fraction, and the matrix properties. CFRP provides high tensile strength and stiffness, but unlike steel, does not yield; this means failure may be more sudden if not managed appropriately.

B. CFRP–Concrete Interface and Bond Mechanics

The performance of CFRP strengthening largely depends on the bond between the CFRP layer and the concrete surface. The adhesive, surface preparation, and the concrete substrate all influence this interface.

Bond-slip behaviour: The interface often follows a characteristic bond-slip law; under load, slippage begins and eventually leads to debonding.

Debonding modes: Common failure modes include interfacial failure, peeling (concrete cover peeling), or adhesive failure. For HSC, the denser, stiffer substrate can change how stresses distribute, potentially leading to different debonding behaviour.

Durability: Environmental exposure (e.g., moisture, temperature cycles) can degrade the bond. Long-term studies are needed to understand how the CFRP–HSC interface behaves under realistic conditions.

III. EXPERIMENTAL INVESTIGATIONS

A. Flexural Strengthening Studies

* A significant recent review by Jahami and Issa (2024) covers how CFRP improves flexural capacity of RC beams, including modelling and failure behaviour. [1]

* In a full-scale experimental study, RC beams (6 m in length) strengthened with CFRP strips using **prestressed** and **passive** systems (including mechanical anchorage) showed that prestressing (up to 50% of CFRP tensile strength) significantly increases moment capacity. [2]

* Another experimental work (conference) showed that increasing the number of CFRP sheet layers enhances bending capacity, though not linearly; also, sustained loads influence rigidity. [3]

B. Shear Strengthening in HSC

* In high-strength concrete elements, external CFRP strips have been used to strengthen shear faces. An experimental study combined with nonlinear FE analysis (LS-DYNA) demonstrated debonding failure and was used to simulate crack propagation and failure. [4]

* Though many shear-strengthening studies focus on FRP more generally, there is limited but growing data on CFRP in high-strength concrete contexts.

C. Recent High-Strength Concrete Beam Studies

* A 2025 study tested high-strength concrete (55–67 MPa) beams reinforced with CFRP bars, also using recycled concrete aggregate (RCA). The beams were tested under different shear-span-to-depth (a/d) ratios, showing varied failure modes (from shear to flexure) and highlighting ductility trends. [5]

* Such experiments provide insight into both strengthening performance and sustainability (RCA use) in HSC + CFRP systems.

IV. ANALYTICAL AND NUMERICAL MODELING

A. Analytical Models

* Semi-empirical and code-based models (e.g., based on ACI 440, fib) remain common for predicting the capacity (flexure, shear) of CFRP-strengthened beams.

* However, HSC introduces complications: models must consider effective bond length, debonding criteria, and potential brittleness. The review by Jahami & Issa highlights that some code predictions may not capture the full behaviour in HSC systems. [1]

B. Finite-Element Modeling

* Finite Element (FE) methods have been widely used to simulate CFRP-strengthened beams. For example, LS-DYNA was used to model debonding behaviour in HSC + CFRP shear-strengthened members. [4]

* FE models can incorporate non-linear material behaviour (concrete cracking, adhesive layer, bond-slip laws), allowing parametric studies (e.g., number of CFRP layers, adhesive thickness, anchorage detail).

V. FAILURE MECHANISMS

Flexural Failure: With CFRP strengthening, failure may shift from yielding of internal steel reinforcement to CFRP rupture or interface debonding.

Debonding: A frequent failure mode, especially at the ends of CFRP strips or sheets. In HSC, higher stiffness could concentrate stresses near the ends, accelerating debonding.

Shear Failure: When CFRP is used for shear, premature debonding or concrete crushing can occur, especially if the bond is weak or anchorage is insufficient.

Brittleness: HSC's brittle nature can reduce ductility; CFRP strengthening can also exacerbate this unless designed for ductility (e.g., using anchorage, graded CFRP strain).

VI. DURABILITY AND LONG-TERM PERFORMANCE

Environmental Degradation: Moisture ingress, temperature fluctuations, freeze-thaw cycles, and UV exposure may degrade the adhesive bond over time.

Fatigue / Repeated Loading: Many RC structures experience cyclic or repeated loads (traffic, wind, seismic); long-term fatigue behaviour of CFRP–HSC interface is not yet fully understood.

Anchorage Strategies: Using mechanical anchors (e.g., U-wraps, bolts) or surface treatments can delay or prevent premature debonding and improve durability.

VII. DESIGN CONSIDERATIONS AND PRACTICE

Design Codes: Design provisions (e.g., ACI 440) guide CFRP strengthening, but may not fully cover HSC-specific behaviours. Engineers must account for bond behaviour, failure modes and potential brittle failure.

Optimization: Deciding the number of CFRP layers, their layout (e.g., strips vs wraps), effective length, and anchorage is critical. Prestressing CFRP is a powerful strategy but requires careful control and design.

Surface Preparation: Proper cleaning, roughening, priming of concrete surface ensures good bond.

Cost-Benefit Trade-off: Although CFRP is expensive, its high performance and potential to extend life of existing structures can justify cost when optimized.

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

1. **More HSC-Specific Tests:** There is a need for more experimental studies on full-scale HSC beams (flexure, shear) with CFRP strengthening under varied conditions (static, cyclic, fatigue, environmental).

2. **Interface Modeling:** Better bond-slip models tailored for HSC are needed, capturing the influence of high density, microstructure, and fracture behaviour.

3. **Durability Studies:** Long-term exposure tests (moisture cycles, freeze-thaw, UV) plus fatigue tests to assess how bond degrades.

4. **Advanced Numerical Models:** Use of multi-scale or cohesive-zone models in FE simulations to more accurately predict debonding initiation and progression in HSC.

5. **Novel Strengthening Techniques:** Research into prestressed CFRP systems, hybrid FRP (e.g., combining CFRP with other fibers), and anchorage innovations.

6. **Data-Driven Design:** Incorporation of machine learning or AI (e.g., neural networks) to predict strengthening outcomes and optimize CFRP layouts; recent work on metaheuristic-ANN prediction of CFRP-confined concrete shows promise. ([arXiv][6])

7. **Code Development:** Based on research, updating or extending CFRP-strengthening design guidelines to better handle HSC nuances, failure mechanisms, and long-term performance.

IX. CONCLUSION

CFRP strengthening offers a highly effective method for enhancing the structural capacity of high-strength concrete beams. While the benefits — such as increased flexural and shear strength — are clear, HSC’s unique material behaviour (high stiffness, brittleness) demands careful consideration in design and application.

Experimental, analytical, and numerical studies collectively demonstrate significant potential, but also highlight challenges: debonding, reduced ductility, and long-term interface degradation. Addressing these through future research — especially focused on HSC-specific behaviour, bond mechanics, and durability — is critical to fully realize the advantages of CFRP in strengthening HSC structures.

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