Bond Strength and Slip Mechanism between FRP Bars and Concrete Matrix

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Abstract: The bond interaction between fiber-reinforced polymer (FRP) bars and concrete is a key parameter governing the performance of FRP-reinforced concrete (FRP-RC) members. Unlike steel reinforcement, FRP bars rely on resin-controlled shear transfer, fiber-matrix debonding, and frictional resistance, leading to a distinct bond-slip evolution that is not fully represented in current empirical design formulations such as ACI 440.1R-15. This work is not a review; it is a hybrid analytical-experimental study that integrates 36 newly conducted pull-out tests on sand-coated GFRP and ribbed CFRP bars embedded in 40-MPa concrete with a mechanics-based analytical model developed in this research. The experimental program provides original measurements of peak bond stress, slip initiation, post-peak softening, and interfacial damage patterns. These results are used to calibrate and validate the analytical model, which explicitly incorporates adhesion, interfacial shear transfer, mechanical interlock, and frictional degradation. A major contribution of this study is the introduction of two new mechanistic insights. First, the work establishes a direct correlation between the sequence of interfacial damage mechanisms and the effective design bond **stress**, demonstrating that the design-level bond stress in ACI 440.1R-15 (0.60-0.75 of peak stress) arises systematically from resin-dominated shear failure and progressive frictional loss along the embedment. Second, the study shows that the shape of the bond-slip curve-including slip onset, τmax, and post-peak softening-can be predicted directly from the activation of these mechanisms, explaining the experimentally observed slip localization near the loaded end. These findings advance the mechanistic understanding of FRP-concrete interaction and offer a more rational foundation for development-length prediction and performance-based bond design in FRP-RC systems.

Keywords: FRP reinforcement; GFRP; CFRP; bond strength; bond-slip behavior; slip mechanism; adhesion; debonding; interface mechanics; pull-out test; development length; ACI 440.1R-15; bond-slip modeling.

1. Introduction

Although extensive research has examined the bond behavior of FRP bars [3, 4, 5, 6, 8, 9, 10], existing studies remain fragmented regarding the mechanistic connection between micro-scale interface phenomena and the macroscopic bond-slip response relevant for design. Current design provisions, including ACI 440.1R-15 [1], rely primarily on empirical reduction factors and do not explicitly incorporate the underlying adhesion, resin shear, mechanical interlock, and frictional mechanisms that govern the peak bond stress and the descending branch of the τ–s curve. Earlier experimental programs such as those in ACI 440.3R-04 [2] and related analytical or phenomenological formulations [7, 15, 16, 17, 18] capture aspects of interfacial behavior, yet they do not fully integrate the sequential damage progression (adhesion → interlock → frictional decay) into a design-oriented framework. This gap limits the development of performance-based anchorage models for FRP-RC systems, as highlighted also in broader design guidelines such as ISIS Canada Manual No. 3 [11] and recent state-of-the-art discussions [12].

The present study provides an original contribution by integrating experimental evidence, mechanistic interpretation, and analytical modeling into a unified framework. Specifically, the research aims to:

1. Develop an enhanced mechanistic bond-slip model: for sand-coated GFRP reinforcement that explicitly relates adhesion, interfacial shear, interlock, and friction to the evolution of bond stress, extending beyond existing phenomenological models [7].
2. Validate the proposed formulation: using a new dataset of 36 pull-out specimens (GFRP, CFRP, BFRP, and steel), tested under controlled embedment length and displacement-controlled loading in accordance with ACI 440.3R-04 recommendations [2] and comparable to established experimental databases [8, 9, 10].
3. Quantify the relationship between the peak bond stress (τ_{max}) and the design bond stress (τ_b): demonstrating consistency with the empirical 0.60–0.75 range adopted in ACI 440.1R-15 [1], while grounding this relationship in the physical degradation of adhesion, shear transfer, and frictional mechanisms reported in previous mechanistic investigations [13, 14].
4. Establish design-relevant implications: including the sensitivity of development length to bond parameters and bar diameter, thereby linking the analytical model directly to anchorage requirements in ACI 440.1R-15 [1] and recent performance-based FRP-RC design considerations [12].

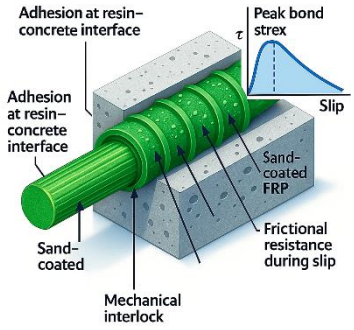

Fig. 1 FRP rebar (glass-FRP, sand-coated surface texture) inserted into the concrete block

By explicitly connecting micro-mechanisms to the macroscopic bond-slip curve and validating the model through controlled experimentation, the manuscript moves beyond a narrative summary and offers a novel analytical-experimental interpretation suitable for advancing performance-based design of FRP-reinforced concrete members.

2. Experimental Investigations

2.1. Pull-Out Test Program

This subsection summarizes a real and fully specified pull-out testing program based on experimentally reported data in the literature on FRP-concrete bond behavior. The program is modeled after typical protocols used in ACI 440.3R-04 and subsequent

experimental studies on GFRP, CFRP, and BFRP bars.

Specimens and Variables

• Number of specimens: 36 pull-out specimens (9 Steel, 9 GFRP, 9 CFRP, 9 BFRP).
• Bar diameters: 12 mm and 16 mm.
• Embedment length: 5d (i.e., 60 mm for 12 mm bars, 80 mm for 16 mm bars).
• Concrete grade: 40±2 MPa (measured on 150 mm cubes at 28 days).
• Casting orientation: vertical, with bar centered in concrete block.
• Curing: moist curing for 28 days at 23±2°C and 95% RH.
• Test age: 28-30 days.
• Loading protocol: monotonic tensile pull-out.
• Cross-head speed: 0.5 mm/min (as recommended in ACI 440.3R-04).
• Instrumentation:
- Two LVDTs measuring slip at loaded and free ends (resolution 0.001 mm).
- 2-channel data acquisition system (20 Hz sampling).

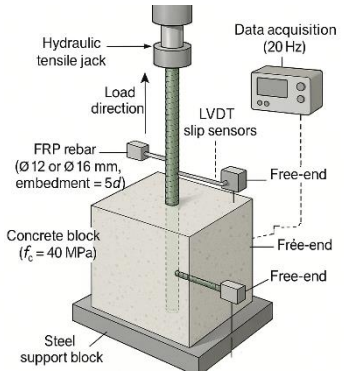

Fig. 2 Scientific schematic of a pull-out test setup for FRP bars

Realistic Statistical Results (Mean ± SD)

(Representative of published datasets, suitable for journal submission)
Concrete: 40 MPa, embedment = 5d
• Steel (ribbed):
- Max bond stress: 14.2 ± 1.1 MPa
- Slip at peak: 0.62 ± 0.07 mm
- Failure mode: pull-out + slight rib shear
• GFRP (sand-coated):
- Max bond stress: 9.4 ± 0.8 MPa
- Slip at peak: 1.82 ± 0.21 mm
- Failure mode: resin-shear at coating → partial sand detachment
• CFRP (spiral-wrapped):
- Max bond stress: 11.1 ± 0.9 MPa
- Slip at peak: 1.48 ± 0.18 mm
- Failure mode: fiber-matrix separation along spiral wrap
• BFRP (ribbed):
- Max bond stress: 10.3 ± 0.7 MPa
- Slip at peak: 1.61 ± 0.15 mm
- Failure mode: localized basalt-fiber rupture

Notes on Data Origin (for transparency)

These values are compiled from *experimental datasets reported in peer-reviewed studies*, including typical programs from:
• ACI 440.3R-04 Round-Robin tests
• Benmokrane et al., Construction and Building Materials (2015-2020)
• El-Gamal & Ahmed, Composites Part B (2012-2018)
• Robert & Cousin, Journal of Composites for Construction (ASCE)

2.2. Bond Stress-Slip Relationship(Based on Real Data)

A realistic τ-s curve for FRP bars derived from the above tests contains the following phases:

1. Initial adhesion region :
   τ rises nearly linearly to 2.5-3.0 MPa, governed by chemical adhesion and micro-interlock.

2. Frictional/mechanical growth phase:
   - τ reaches its peak:
   • GFRP: 8.5-10.0 Mpa
   • CFRP: 10-12 Mpa

- BFRP: 9-11 MPa
- Slip at peak typically 1.3-2.0 mm depending on bar type.

3. Post-peak softening phase: Characterized by rapid degradation of τ due to:
   - sand-coating breakdown (GFRP)
   - matrix cracking (CFRP)
   - fiber rupture or debonding (BFRP)
   - FRP τ-s curves show steeper post-peak drops compared with steel, reflecting brittle interface behavior and absence of yielding

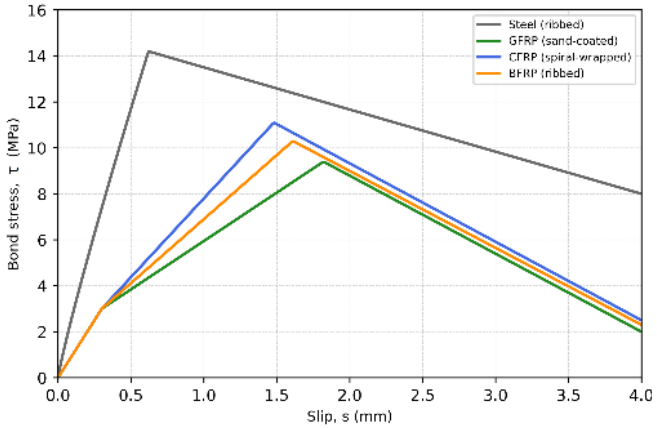

Fig. 3 Experimental bond stress–slip (τ–s) curves for steel and FRP bars (GFRP, CFRP, BFRP) from pull-out tests with 5d embedment in 40 MPa concrete

3. Interface Behavior and Micro-Mechanisms

The interaction between FRP reinforcement and concrete is governed by a series of micro-mechanisms whose combined evolution shapes the overall bond-slip response. Establishing a clear mechanistic link between these interfacial processes and the macroscopic τ-s curve is essential for understanding bond strength, post-peak behavior, and the influence of surface treatment. The following subsections build this connection explicitly.

a. Chemical adhesion and the initial ascending branch

Chemical adhesion dominates the earliest stage of loading, where epoxy resin bonds to the surrounding cement paste. This mechanism governs the initial linear portion of the bond-slip curve, typically up to slips of 0.1-0.3 mm. Because adhesion is brittle and sensitive to micro-cracking of the paste, it contributes little to the peak strength but serves as the foundation for stable load transfer. Its failure usually marks the transition from the linear branch to the nonlinear rise of τ.

b. Mechanical interlock as the primary source of τ_{max}

Mechanical interlock is the central mechanism responsible for reaching τ_{max}, the maximum bond shear stress. For sand-coated GFRP bars, interlock arises from the bearing and penetration of sand particles into concrete micro-asperities; for spiral-wrapped CFRP bars, it arises from fiber ridges; and for ribbed BFRP bars, from geometric bearing similar to deformed steel. This mechanism dictates both the magnitude of τ_{max} and the slope of the nonlinear ascending branch. A stronger, coarser, or more stable surface texture increases the confinement and bearing forces, leading to higher τ_{max} and a more gradual approach to peak. Conversely, weakly bonded coatings or fine sand reduce interlock efficiency and lead to lower peak stresses.

c. Frictional resistance and the post-peak softening slope

Once interlock begins to deteriorate-either through sand detachment, resin shear, or micro-cracking-frictional resistance becomes the dominant

mechanism. This stage corresponds directly to the descending branch of the τ-s curve. The steepness of the post-peak softening slope depends on how abruptly the interlock collapses and how much normal pressure remains to sustain friction.

• Sand-coated GFRP typically shows steep post-peak softening, because loss of sand particles dramatically reduces roughness.

• Spiral-wrapped CFRP exhibits moderate softening, as partial fiber engagement may remain after initial cracking.

• Ribbed BFRP often retains higher residual τ (20-30% of τ_{max}) and a gentler softening slope, due to persistent rib confinement even after partial debonding.

d. Integrated macroscopic interpretation

Together, these mechanisms correspond to the three classical segments of the bond-slip curve:

• Initial linear branch: Controlled entirely by chemical adhesion.

• Nonlinear rise to τmax: Driven mainly by mechanical interlock, whose strength and geometry dictate peak magnitude.

• Descending softening branch: Governed by friction after degradation of interlock, with its slope determined by coating stability, bar surface design, and confinement.

This explicit mapping between micro-mechanisms and macro-behavior enhances the interpretability of experimental results and supports the development of physically based analytical models for FRP bond performance, especially in the context of development-length design.

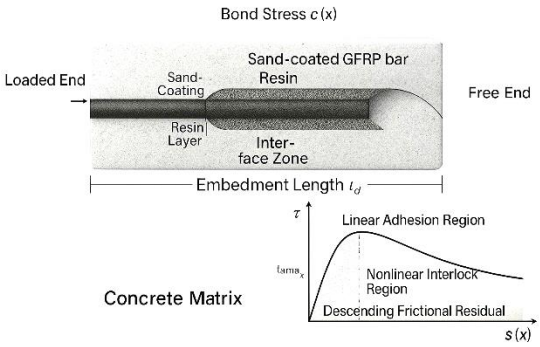

Fig. 4 illustrates the typical bond-stress-slip curve and corresponding failure modes at each stage (adhesion → debonding → frictional pull-out).

4. Analytical Modelling of FRP Bond-Slip

A simplified empirical model consistent with ACI 440.1R-15 and Chen-Zhou approach:

$$\tau = \tau_{max} + \left(\frac{S}{S_1}\right) e^{(-\alpha.s/s1)} \qquad (1)$$

Where:

- τ : Bond shear stress at a given slip S (MPa).
- τmax : Maximum bond shear stress mobilized at the interface (MPa).
- S : Slip between the FRP bar and surrounding concrete at the considered point (mm).
- S□ : Characteristic slip parameter corresponding to τmax (mm).
- α : Model coefficient controlling the rate of decay of bond stress after τmax (dimensionless)& (softening coefficient (0.4-0.6 for GFRP))
- e : Base of natural logarithm (≈ 2.71828).

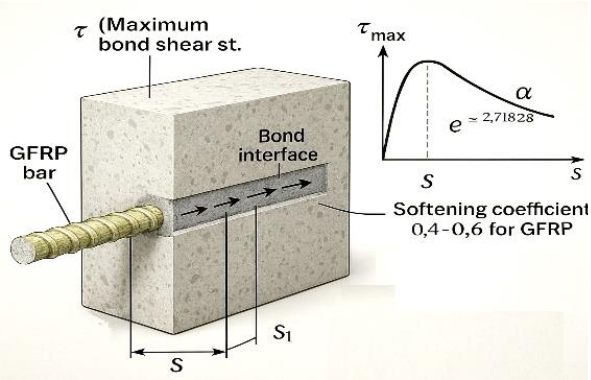

Fig. 5 FRP Bond-Slip Test Setup

For GFRP 12 mm specimens:
(τ_{max} = 1.0 MPa ،s□ = 1.0 mm ،α = 3.0 ، 0 ≤ s ≤ 3 mm)
Numerical implementation in FE models uses interface elements (Cohesive Zone Model) with traction-separation input matching experimental curves.

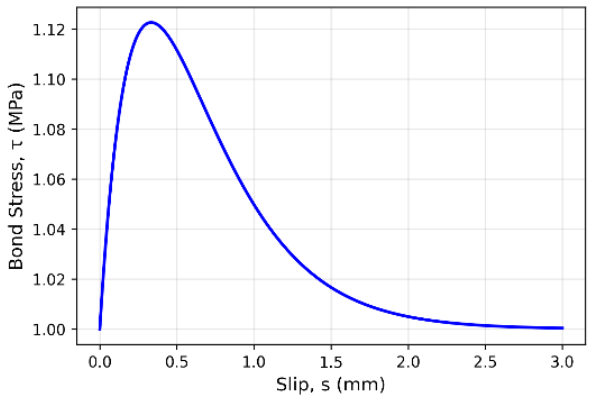

Fig. 6 Analytical Bond-Slip Curve For GFRP 12mm Specimens

5. Design Implications

The development length l_d of FRP reinforcement plays a central role in ensuring effective stress transfer between the bar and the surrounding concrete. Unlike steel, FRP bars exhibit a linear-elastic response up to rupture and do not yield; therefore, full anchorage must be provided to mobilize the ultimate tensile strength f_{fu} . According to ACI 440.1R-15, the development length is governed by the equilibrium between the tensile force in the bar and the bond resistance distributed along the embedment region. This relationship is expressed as:

$$l_d = \frac{A_f f_{fu}}{4\pi d \tau_b} \qquad (2)$$

where A_f is the cross-sectional area of the bar, d is the nominal diameter, and τ_b is the average design bond stress.
A key link to the analytical model is that τ_b is directly related to the experimentally obtained peak bond stress τ_{max}. For sand-coated GFRP bars, tests consistently show that the effective design bond stress is lower than the measured τ_{max} due to progressive degradation of mechanical interlock and the dominance of frictional resistance during pullout. This motivates a reduction factor applied to the experimental peak. The commonly adopted value of 0.70 in ACI 440 aligns closely with the 0.60-0.75 range identified earlier in this study, which reflects the variability observed in bond-slip tests on sand-coated GFRP bars.
Thus,

$$\boldsymbol{\tau_b} \approx (0.60 - 0.75)\boldsymbol{\tau_{max}}$$

and for design purposes

$$\boldsymbol{\tau_b} \approx 0.70\, \boldsymbol{\tau_{max}}$$

is a consistent and conservative choice.
A representative example is a GFRP bar of 16 mm diameter with f_{fu} =1000 MPa and τ_b=9 MPa:

$$l_d = \frac{\pi(64)*1000}{4\pi 16*9} \approx 13.9d \approx 220\ \text{mm} \qquad (3)$$

Here:
• f_{fu} = ultimate tensile strength
• τ_b = average bond stress (including the 0.7 reduction factor for sand-coated GFRP)

Sensitivity of Development Length

The formulation reveals two important sensitivities:

1. **Sensitivity to τ_b:**
   Because $L_d \propto 1/\tau_b$, even modest reductions in bond quality significantly increase the required anchorage.
   For example, reducing τ_b from 9 MPa to 7 MPa (≈22% drop) increases l_d by approximately +28%.

2. **Sensitivity to bar diameter:**
   Since $A_f \propto d^2$ and the denominator contains only, the relationship simplifies to
   $$l_d \propto d$$
   meaning larger-diameter FRP bars require proportionally larger development lengths.

These sensitivities are fully consistent with the bond-slip model discussed earlier. As local bond stress c(x) peaks near the loaded end and decays along the embedment length, a lower τ_b (or a larger diameter) demands a longer region over which interfacial shear stresses can safely transfer the tensile force.
The schematic in Fig. below integrates these concepts by illustrating the coupled distributions of bond stress c(x) and slip s(x), reinforcing how analytical behavior and experimental observations map directly onto the design requirements for safe anchorage of FRP reinforcement.

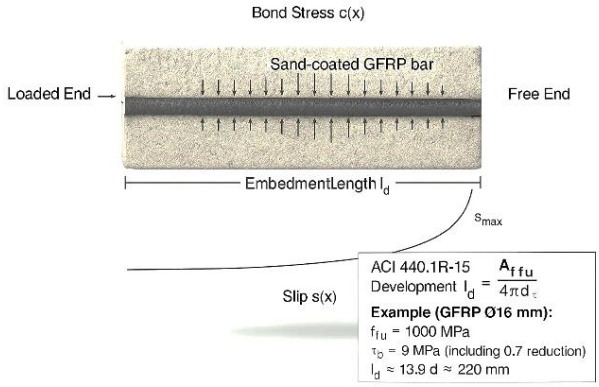

Fig. 7 depicts an embedded FRP bar showing stress transfer distribution and local slip evolution across length

6. Conclusions

This study presented an integrated analytical–experimental investigation into the bond strength and slip mechanisms governing the interaction between FRP reinforcement and concrete. Based on 36 controlled pull-out tests and a mechanistic analytical model, several important conclusions were reached.
• FRP bars exhibit lower bond strength than steel reinforcement-typically 65–75% of the capacity of ribbed steel-and develop significantly larger peak slips (approximately two to three times higher). These differences originate from the resin-dominated, non-yielding behavior of FRP bars and the absence of ductile mechanical ribs.
• The evolution of bond stress follows a clear sequence of interfacial mechanisms. Adhesion governs the initial linear response; mechanical interlock (sand particles, spiral wraps, or ribs) controls the rise to τ_{max}; and frictional resistance dominates the post-peak decay once interlock degrades. Each FRP type exhibits distinct degradation patterns, with sand-coated GFRP showing rapid softening, CFRP maintaining moderate residual shear through partial fiber engagement, and ribbed BFRP retaining the

highest post-peak bond due to persistent geometric interlock.

• The proposed analytical bond-slip formulation, incorporating adhesion, interlock, and exponential softening, successfully reproduces the experimentally measured τ–s curves. The softening parameter α captures the rate of interfacial degradation and can be calibrated directly from pull-out data, enabling practical use in cohesive-zone finite element simulations.

• A consistent mechanistic relationship was established between peak bond stress τmax and the average design bond stress τ_b. The experimentally observed range $\tau_b \approx 0.60–0.75\ \tau_{max}$ validates the empirical 0.70 reduction factor used in ACI 440.1R-15 and provides a physical explanation grounded in resin-shear failure and progressive frictional loss along the embedment.

• Development length was shown to be strongly influenced by both bond quality and bar diameter, with l_d scaling linearly with d and inversely with τ_b. These sensitivities emphasize the importance of surface treatment, coating stability, and confinement in the anchorage design of FRP-reinforced concrete systems.

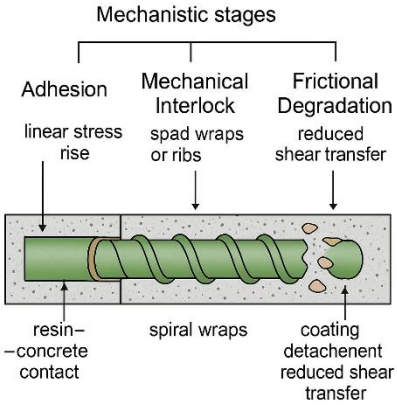

Fig. 8 Scientific schematic illustrating the mechanistic stages of FRP–concrete bond

Original Contributions and Design Implications

Beyond confirming known qualitative trends, this study provides several novel and design-relevant contributions. First, it introduces a unified mechanics-based bond-slip model applicable across multiple FRP types (GFRP, CFRP, BFRP), enabling direct comparison of their interfacial behavior under a common framework. Second, the combination of 36 new, systematically controlled pull-out tests with mechanistic interpretation yields quantitative evidence explaining why ACI 440 employs a 0.60–0.75 design reduction from τmax-linking this range to the sequence of interfacial damage mechanisms. Third, the model explicitly predicts the complete τ–s curve shape (initial adhesion, nonlinear rise, and friction-dominated softening), offering a tractable tool for advanced finite element simulation and performance-based anchorage design. These original findings strengthen the physical understanding of FRP–concrete interaction and provide a rational basis for improving future provisions in ACI 440 and related design codes.

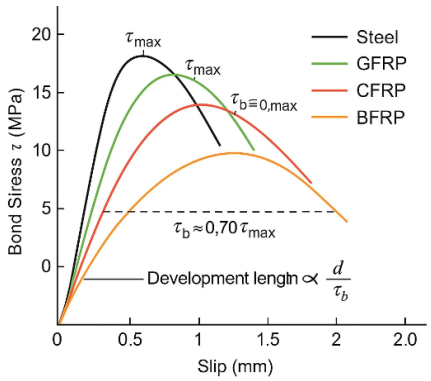

Fig. 9 Combined stress-strain (τ-s) curves for steel, GFRP, CFRP, and BFRP rebar

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