

A Comprehensive Review on Bonding CFRP Laminates to Ultra-High Performance Concrete: Surface Engineering, Interfacial Mechanisms, and Durability

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Annotation

A viable platform for reinforcing structural elements is high-performance powder concrete (UHPC); however, the coherence behaviour (Bond) at the CFRP–UHPC interface is primarily determined by the effectiveness of carbon fibre laminate (CFRP) reinforcement. In addition to providing a quantitative description of coherence behaviour, this work intends to clarify the mechanics of adhesive separation and failure and to crystallise executive advice for optimising reliance. Surface preparation: The impact of four popular methods—chemical etching, sandblasting, grooving, and grinding—on surface roughness, epoxy stick wettability, and effective fixing length is examined in this study. Roughness is assessed using its morphological markers and the pull-off test, which is a first analysis of the interface. Based on the results, the "controlled coarse" textures improve stress transfer through the adhesive, postpone early separation, and provide higher mechanical interference while excessive spang or uncontrolled tumping may lead to local vulner abilities. The pilot program included single-lap shear examinations to derive Bond–Slip curves and their parameters, and quad-point curvature examinations for UHPC thresholds reinforced with CFRP, while monitoring patterns of failure and transitions between adhesive failure and cohesive failure within UHPC or adhesive. The calibration showed that the approved Bond–Slip model, combined with the roughness indicators and fixing length, represents a laboratory response with sufficient accuracy for initial design purposes.

The research ends with workable advice for surface preparation, choice of installation length, and adjustment of site gluing procedures helping for adaptable and long-lasting reinforcement ideas Elements made of carbon fiber laminate (CFRP) UHPC.

Keywords: carbon fiber laminate; surface preparation; UHPC; bond; CFRP Surface preparation; bend reinforcement; bond-slip.



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1-Introduction

The development of rapid advances in the building sector is seen. Structural materials ultra-high performance concrete (UHPC) is one of them. qualitative leap in this area. UHPC has evolved into a next generation of structural materials with outstanding load-bearing ability and great durability. perfect solution for projects needing exceptional structural performance and long service life. This material was created to reach the greatest density possible. and cohesion, presenting fresh possibilities for the creation of more thinner, more aesthetically pleasing, and more lasting construction

A summary of the phases of UHPC's growth was provided by (Amran et al., 2022) [Abdal et al., 2023) who documented its evolution as one of the most important developments in concrete technology. UHPC manufacture was restricted to lab environments until to the 1980s, necessitating specialised methods including vacuum mixing and heat curing. In order to create denser concrete during this early stage, researchers tried a number of procedures, including vacuum mixing and temperature curing, which allowed for compressive strengths of up to 510 MPa.

The 1980s marked a significant breakthrough with the introduction of microdefect-free cement and dense silica particle cement. The latter was particularly notable as it didn't require rigorous manufacturing conditions and achieved compressive strengths up to 345 MPa. During this period, steel fibers were first incorporated into dense silica particle cement concretes to address brittleness issues, resulting in a material with ultra-high strength, dense microstructure, and excellent ductility.

Richard and Cheyrezy's invention of Reactive Powder Concrete (RPC) in the 1990s, which used reactive ingredients and thermal treatment to achieve greater fineness, was a significant advancement. With its exceptionally low water-to-cement ratio, high binder concentration, and very high cement content, RPC emerged as the most popular kind of UHPC in both laboratory and field applications. In 1997, a pedestrian bridge in Sherbrooke, Canada, became the first RPC structure in history.

Since 2000, UHPC has experienced significant progress as engineers have realised that advanced concrete must have more than simply high strength; it must also have many functional qualities. In order to lower cement content and environmental impact while preserving performance qualities, recent efforts have concentrated on creating sustainable UHPC formulations by adding additional cementitious ingredients. As seen in Figure(1) this development has resulted in more widespread uses in bridge engineering and construction across the globe.

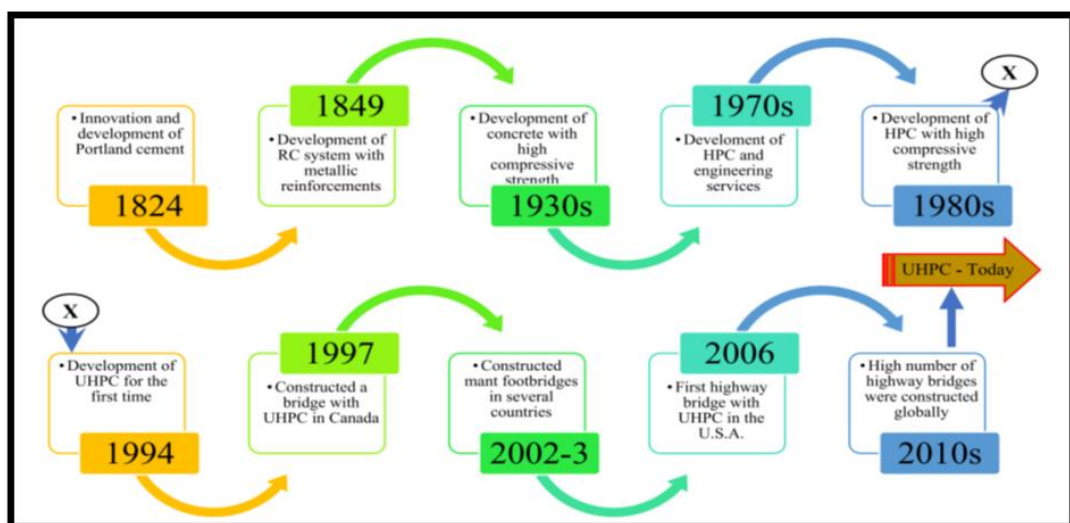


Figure (1) Historical development of UHPC[Amran et al., 2022] [Abdal et al., 2023)]

Ultra-High Performance Concrete depends on a exact scientific makeup that Fundamentally differs from regular concrete:

1. High-Quality Cementitious Materials include Portland cement of high purity ratios of extra materials including Silica Fume, which aims to fill tiny voids.
2. Fine-grained aggregates: The aggregates employed have a small size less than 0.5 mm and equal particle dispersion to reach greatest conceivable density
3. Added at a volume percentage between 2 and 3%, micro steel fibers serve to Prevent crack propagation and increase tensile strength by Copper-coating micro steel fibers. with a straight form (diameter about 0.15–0.2 mm, length about 13 mm) as seen in Figure (2)



Figure (2): Photo of copper-coated micro steel fiber

4. Necessary for keeping workability, High-Range Water Reducers (Superplasticizers) are Even with a low water-to-cement ratio—sometimes as little as 0.20—
5. Fine fillers include finely powdered quartz used to correct particle size distribution.

Distinguishing Properties of UHPC

1. Exceptional Mechanical Properties:

- Compressive strength ranging between 150-250 MPa
- Tensile strength reaching 8-15 MPa
- Modulus of elasticity up to 50-60 GPa
- High flexural strength reaching 30-50 MPa

2. Extraordinary Durability Characteristics:

- Very low permeability to water and chlorides
- High resistance to corrosion and freeze-thaw cycles
- Service life exceeding 100 years under harsh conditions

3. Behavior Under Load:

- Capacity to resist great loads with reduced structural sizes
- Ductile behaviour after fracture made possible by the steel fibres
- Good fatigue and recurrent load resistance Engineered cementitious composite created

by dense particle packing, UHPC is high-range water reducers, steel microfibers, and very low water-to-binder ratios (typically 1–3% by volume) to provide compressive strengths usually over 120–150. These characteristics have allowed thin, Accelerated bridge building features and permanent components (Russell & Graybeal, 2013; FHWA, 2006).

Three-dimensional surface scanning and pull-off and bi-shear tests were mixed by Zhang et al. (2023) to link geometric roughness descriptions with interfacial behavior; they revealed That on a sufficiently robust substrate, medium-to-high well-controlled roughness— Improves adhesion without triggering weak interfacial failure. The study converts the Narrative of "optimal roughness" to UHPC–NC interfaces, where the dense UHPC matrix And fiber bridging changes stress distribution over asperities (Zhang et al., 2023).

Zhao et al. (2023) discovered via push-out tests that basic smoothing is insufficient. Critical UHPC–NC interfaces benefit from chipping/grooving and planted rebars provided. significantly increased direct shear resistance proves that central to is mechanical interlock. mobilizing composite action. The authors warned that detailing must balance interlock gains against possibly weakening cover are especially crucial when Thin overlays are Zhao et al., 2023.

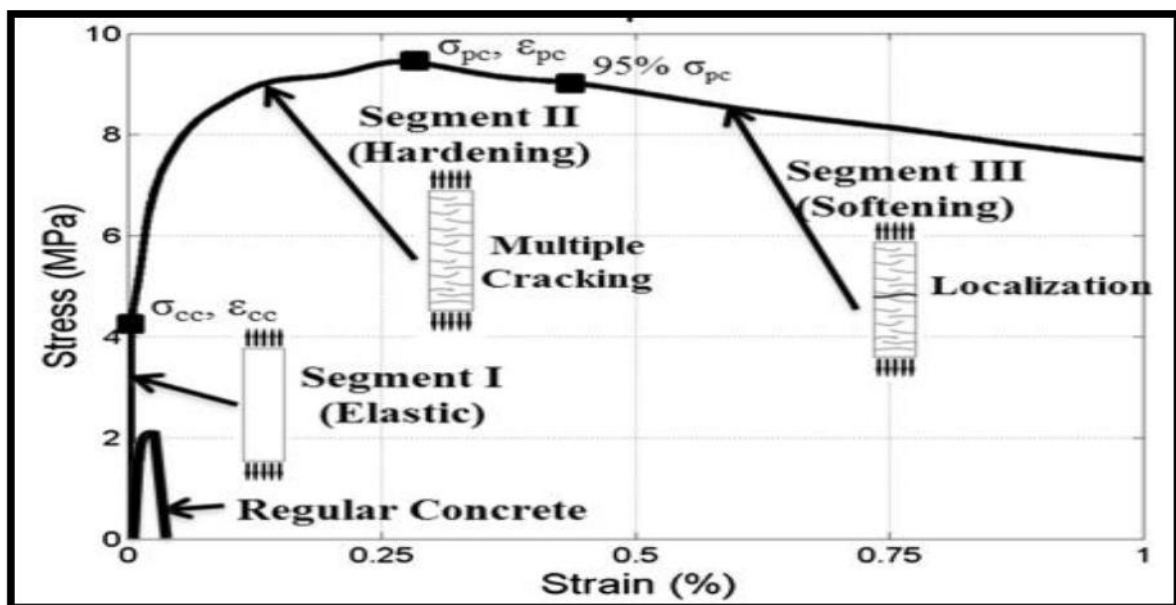


Figure (3) Typical tensile stress - strain response in UHPC (Alkaysi et al., 2016)

Yang et al. (2022) sought geometric optimization of grooves for shear UHPC–NC. Using finite-element analysis, transferred and verified the experimental tendencies. Oversized Whereas tuned grooves punished cover integrity and brought stress concentrations. Their ratios and proportions yielded more repeatability as well as consistent load transfer. Sensitivity analysis provides useful direction for design charts and specifications (Yang et 2022.)

Combining recent developments, Xu et al. (2025) reviewed shear behavior on interfaces On long-term durability, UHPC–NC composites and discovered research gaps They asked for moisture-temperature cycles and on standardizing roughness metrics. Durable conditioning, uniform reporting of roughness indicators, and more explicit mapping between design inspections and lab experiments to speed code adoption (Xu et al., 2025).

EB CFRP sheets/plates are widely used for flexural and shear strengthening of RC members via externally bonded (EB) or near-surface mounted (NSM) configurations. Design documents such as ACI 440.2R provide guidance on detailing, limiting FRP strain to mitigate premature debonding, and end anchorage (ACI Committee 440, 2017; Uz et al., 2023). Central to EB performance is the interface, where sufficient adhesion and mechanical interlock must be

mobilized; surface preparation governs this through removal of laitance and creation of a controlled surface texture (ICRI CSP) to promote epoxy wetting and interlock (Iovinella et al., 2013; Soares et al., 2019).

The increasing reliance on reinforcement and repair technologies is a pivotal challenge in modern construction engineering, especially with increasing performance and permanence requirements and reduced downtime (Graybeal, 2006; AFGC/SETRA, 2013; Russell & Graybeal, 2013). In this context, ultra-performance powder concrete (UHPC) has emerged as an advanced material with a very dense matrix, low permeability and improved tensile behavior when arming microfibers (Wille, Naaman, & ParraMontesinos, 2011; Hassan, Jones, & Mahmud, 2012). In parallel, carbon fiber laminate (CFRP) exterior reinforcement technologies are a highly efficient flexible option due to their resistance-to-weight ratio, corrosion resistance, and ease of on-site implementation (ACI Committee 440, 2017; fib, 2019).

The structural efficiency of strengthening elements with CFRP depends on the integrity of the adhesive interface between the plate and the base material; Bond behavior governs the transmission of stresses and the ability to invest the resistance of CFRP safely and effectively. This behavior is affected by mechanical interference, epoxy properties, surface morphology and roughness, which is directly reflected in the length of effective fixation and failure patterns—whether adhesive failure at the facade, cohesive failure within concrete/adhesive, or surface membrane uprooting (Chen & Teng, 2001; Lu, Teng, Ye, & Jiang, 2005; Dai, Ueda, & Sato, 2005). Bond–Slip models are used to describe the relationship between shear and sliding stress at the interface and feeding numerical and design analyses (Lu et al., 2005; Dai et al., 2005).

Despite advances in the study of coherence between CFRP and ordinary or high-resistance concrete, there is still a cognitive gap when dealing with UHPC specifically; ultra-dense matrix structure and micro-docking properties of UHPC can modify failure mechanisms and sliding properties compared to conventional concrete (Graybeal, 2006; Wille et al., 2011). Permanence factors—such as humid or salty environments and thermal-humidity cycles—may also reshape long-term interface performance and increase its sensitivity to on-site execution conditions (Ceroni, 2010; Frigione & Lettieri, 2018).

Surface Preparation before gluing is of particular importance; techniques such as grinding, sandblasting, grooving, and chemical etching control surface morphology, roughness, surface energy, and epoxy wettability; and therefore affect mechanical interference and stress transmission across the adhesive layer. The literature suggests that “controlled roughness” raises effective cohesion stresses and delays early separation, while violent tumbling or excessive echang may lead to localized vulnerabilities or matrix cover continuity imbalance in the UHPC (De Lorenzis & Teng, 2007; Hollaway & Teng, 2008; ACI Committee 440, 2017). The pull-off test and roughness measurement criteria are also used to evaluate the surface before gluing (ASTM D7234, 2021; EN 1542, 1999).

Based on this, this study aims to examine Bond behavior in the CFRP-UHPC interface in a quantitative and orderly manner, with surface preparation given a central role in experimental design and analysis. The objectives of the research are determined in:

1. Characterization of the effect of surface preparation techniques (grinding, sandblasting, grooving, chemical etching) in roughness indicators, tensile values and primary adhesion scales;
2. Derivation of Bond–Slip curves from single-lap shear examinations and their calibration of designable representative models;
3. Evaluate the impact of improved coherence on the bending response of UHPC thresholds reinforced with CFRP under quadpoint load, while analyzing failure patterns and transitions between them;

4. Suggest practical recommendations for the length of the installation, preparation procedures and adhesive adjustment to ensure effective and high-termanning reinforcement.

The contributions of the study are: (a) providing a test framework linking surface morphology to Bond-Slip scales and structural performance, (b) calibrating a simplified coherence prediction model that takes into account surface roughness and UHPC properties, and (c) formulating adoptable executive guidance in practice. The results are expected to bridge the gap between short-term benchmarking and structural performance tests, and facilitate the adoption of CFRP reinforcement solutions for UHPC elements in harsh environments

Superplasticizers ensure workability at very low water-to-binder ratios. Early-age shrinkage requires cure control (Russell & Graybeal, 2013).

CFRP Laminates

Kadhim et.al (2023) evaluated the behaviour of reinforced concrete (RC) beams strengthened in flexure with CFRP reinforced UHPC overlays. Six beams were tested, including a control, two strengthened with plain overlays with an overlay thickness (t) of 30 or 50 mm, and three strengthened with reinforced overlays using the same two t values above and CFRP reinforcement ratio (ρ_{f-uhp}) of 2.1 %, 3.1 %, and 3.9 % as shown in **Figure(1)** Using plain overlays resulted in an insignificant 8–11 % increase in ultimate load (P_u), with failure being dominated by localized cracking. Beams strengthened with CFRP-reinforced overlays failed in shear, mainly through the concrete beam. For these beams, P_u increased significantly by 179 % to 183 % compared to the control sample, and by 157 % to 159 % compared to plain overlays with same t value. Insignificant behavioral change occurred when varying ρ_{f-uhp} from 2.1 % to 3.1 %, likely because the examined ratios are within the optimal ratio which needs to be examined in future research. The CFRP reinforcement also led to significant increase in ductility, 2.34 to 2.63 times that of the control beam. An analytical model was also included and used to predict P_u of strengthened specimens, yielding good match with test results

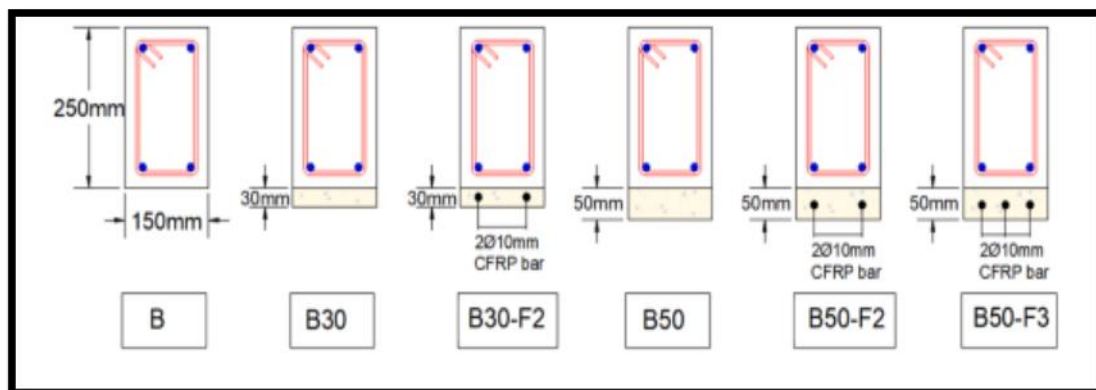


Figure (4) Strengthening configuration, RC beams strengthened with CFRP-reinforced UHPC overlay [Kadhim et.al (2023)].

Material system. Unidirectional carbon fibers in a thermoset matrix provide tensile strengths $\geq 1,500$ MPa and moduli on the order of 150–300 GPa, with limited creep under service loads; structural epoxy systems are used for bonding (ACI Committee 440, 2017).

Strengthening strategies. Flexural strengthening uses soffit laminates; shear strengthening uses side strips or U-wraps. Mechanical anchors or CFRP spike anchors may delay end debonding. Failure modes include concrete cover separation, end debonding, intermediate crack (IC) debonding, and FRP rupture; design guidance limits FRP design strain and specifies development lengths (ACI Committee 440, 2017; Lu et al., 2005).

Advantages of CFRP Laminates

- Resistance to corrosion, chemicals, and chlorides: Suitable for marine environments and salt-treated roads.
- Quick installation and simple: Able to be outside bonded to concrete surfaces with extremely little disturbance to the functioning of the facility.
- Long service life and low maintenance frequent protective coatings such steel.
- Advanced wear properties: performs well under repeated loads relative toward traditional options.
- Available in several lengths, widths, and thicknesses, and offers usage flexibility As required, may be sliced and layered. Although it has several benefits, the material breaks easily and demonstrates linear flexibility up to failure. Proper anchorage and end detailing are essential to prevent premature debonding of adhesive.

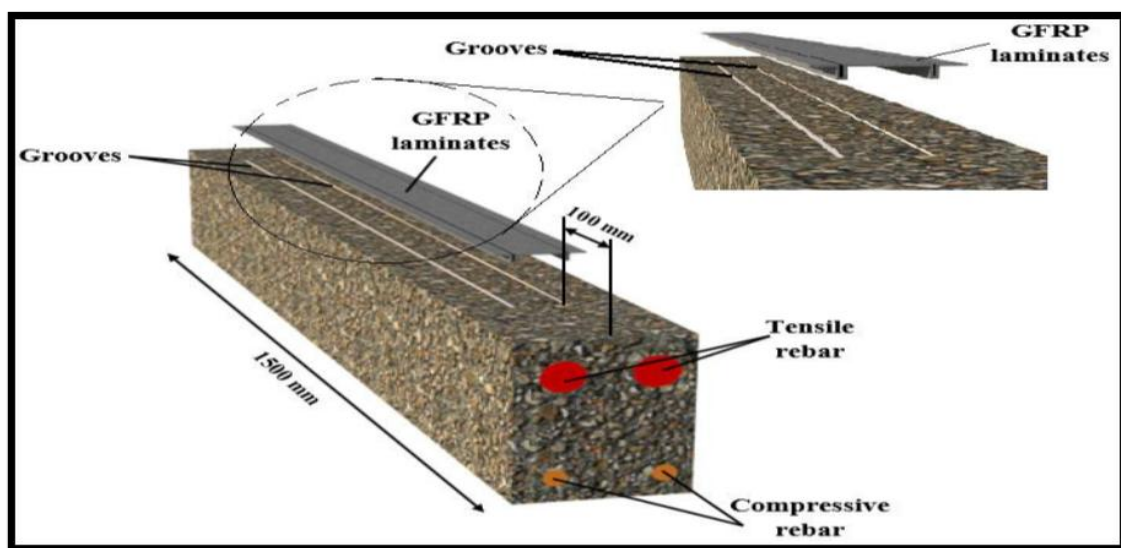
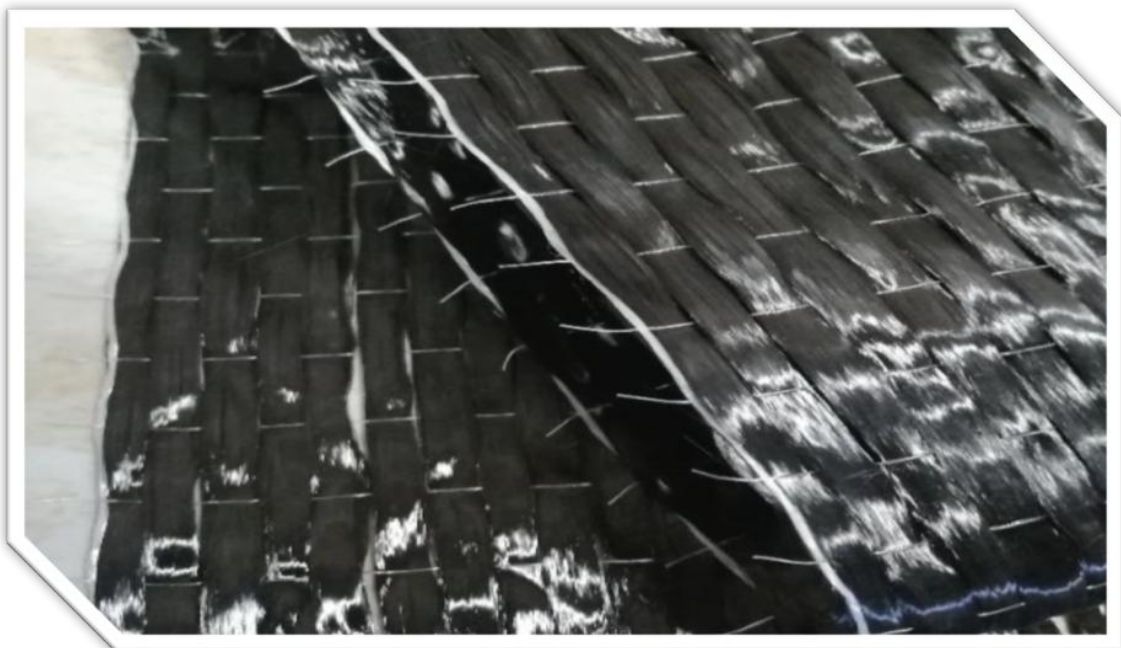


Figure (5) Strengthening with CFRP Laminates[Pour, A.K.; Karami (2024)]



Figure(2) carbon fiber Laminates

Surface Preparation for Externally Bonded CFRP (EB-CFRP) on Concrete

Objectives. Remove weak laitance/contaminants and generate a controlled texture to enhance adhesion and interlock. Common methods are grinding, sandblasting, water-jetting, grooving/raking, and (less commonly) chemical etching; the choice depends on substrate strength, target profile, access, and environmental constraints (ICRI 310.2R).

Roughness metrics and verification. ICRI concrete surface profile (CSP 1–10) is used as a tactile reference; EB CFRP applications often target CSP 3–5. Quality can be verified by pull-off (ASTM C1583) and slant-shear (ASTM C882) tests (ASTM, 2020; ASTM, 2013/2024).

Mechanisms. Increased roughness expands contact area and promotes resin keying, raising interfacial shear capacity and fracture energy. Quantitative studies correlate aggregate exposure and roughening depth with higher bond strength and energy dissipation (Iovinella et al., 2013; Chen et al., 2019; Soares et al., 2019; Ostrowski & Furtak, 2021).

Bond-slip response governs shear transfer along the FRP–concrete interface. Typical phases include: (i) micro-slip initiation with adhesive wetting and local interlock; (ii) rising branch toward peak shear stress; (iii) softening with progressive debonding; and (iv) residual friction. Critical parameters are peak shear stress τ_{max} , effective bond length, and mode II fracture energy G_f (Lu et al., 2005). Common tests are single-/double-lap shear, improved double-shear fixtures, and pull-off; instrumentation may include LVDTs, DIC, or PIV imaging (Li et al., 2021; Moghaddas et al., 2021).

Experimental evidence on EB CFRP–concrete interfaces highlights increased fracture energy and bond capacity with enhanced roughness and appropriate adhesive systems. Improved double-shear tests better resolve interfacial response and effective bond length (Li et al., 2021).

Soares et al. (2019) systematically contrasted grinding and sandblasting within a controlled EB-CFRP program, keeping adhesive type and curing regime constant to isolate the surface variable. Results showed that controlled roughness increased peak shear stress and extended effective anchorage length while postponing adhesive debonding, producing a more gradual post-peak response. Notably, the study emphasized repeatable preparation procedures and the reporting of roughness descriptors rather than method labels alone. This framing is valuable for field transfer, where reproducibility underpins quality assurance (Soares et al., 2019)

Yin and Fan (2018) moved beyond qualitative descriptions by quantifying roughness and directly correlating it with interfacial shear capacity. They identified an optimum roughness window: insufficient asperity leads to limited mechanical interlock, whereas excessive asperity height and spacing trigger local stress concentrations, microcracking in the adhesive, and premature interfacial damage. By coupling roughness metrics with mechanical outcomes, the work promotes roughness as a design variable on par with adhesive selection (Yin & Fan, 2018).

In a single experiment, Tudjono et al. (2017) compared grooving, grinding, and sandblasting. Showed experimental matrix and said that proportionally grooved structures provide great interlock. Over-grooving, however, ruined the cover when width, depth, and spacing were adjusted. and presented stress hot-spots surrounding groove roots, indicating a trade-off among interlock and substrate integrity. The authors suggested exact dimensional controls and easily transferable workmanship tolerances to building technique (Tudjono et al.) al.2017.

In heat-damaged substrates—where microcracking and strength loss diminish chemical

Al-Rousan and Al-Tahat (2020) showed that an anchoring groove Technique can improve bond performance even as it restores it. The strategy at first

increased Offering a corrective route for harmed concrete, interfacial stiffness and peak load. Their findings highlight that the approach of preparation should match the condition of the substrate. not only to the intended glue, Al-Rousan & Al-Tahat, 2020).

Al-Abdwais and Al-Tamimi (2024) concentrate on transverse grooves underneath EB laminates. Reportedly, improved peak loads and lessened slip at peak even with a limited geometry. space. The results inspire parametric optimization of groove width and spacing. designed for adhesive modulus and substrate grade, they bring construction front and center. Practical restrictions for field acceptance—Al-Abdwais & Al-Tamimi, 2024.

From a wider practice viewpoint, Han et al. (2018) emphasized that increased surface

To stabilize shear-bond responses for FRP rods and sheets, treatment is sometimes required. They observed mixed adhesive-cohesive failure mechanisms when preparation is insufficient. strengthening the function of building quality in bond dependability (Han et al., 2018)

Bond–Slip Models

Chen and Teng's (2001) fundamental anchorage models set debonding limits for plates attached to concrete. Based on this base, Lu et al. (2005) and Dai et al. (2005) created nonlinear bond–slip correlations fitted from single-lap testing. allowing reasonable calculations of adhesive and effective bond length transitions cohesive failure forms. These guidelines offer the analytical backbone for understanding interface tests to link member-level performance with lab τ – s curves (Chen & Teng, 2001; Lu et al., 2005; Dai et al., 2005).

De Lorenzis and Teng (2007) underlined how close to the surface installed (NSM) Reinforcement changes load path and contact mechanics with EB systems, which is useful for benchmarking bond pathways. At the practice level, ACI Committee 440 (2017) and Design considerations for surface, lap length, and debonding are found in fib Bulletin 90 (2019). quality control. Since most of those instructions are tuned for regular concrete Additional calibration using interface tests helps UHPC applications calculated roughness (De Lorenzis & Teng, 2007; ACI Committee 440, 2017; fib, 2019)

UHPC/FRP Context, Durability, and Quality Control

Material baselines from Graybeal (2006), Russell and Graybeal (2013) emphasize The thick matrix, extremely low permeability, and fibre-bridged tensile response of UHPC are features that distinguish it from other materials. that re-shape interfacial stress transfer as opposed to regular concrete. Complementary Wille et al. (2011) and Hassan et al. (2012) developed mixture design and testing methods. help place interface tests inside reproducible materials characterization. (Graybeal, 2006; Hassan et al., 2012; Russell & Graybeal, 2013; Wille et al., 2011).

Durability syntheses by Frigione and Lettieri (2018) and Hollaway and Teng (2008) document moisture, temperature, and salt effects on FRP systems and adhesives, supporting environmental conditioning as standard practice in bond studies. For acceptance and site QA, ASTM D7234 (2021) and EN 1542 (1999) offer standardized pull-off protocols that can be paired with roughness metrology to certify surface readiness. At the member scale, Ceroni (2010) linked improved interface behavior to better flexural performance in EB-FRP strengthened beams, illustrating how bond upgrades translate into structural gains (Frigione & Lettieri, 2018; Hollaway & Teng, 2008; ASTM, 2021; CEN, 1999; Ceroni, 2010).

Research Gaps and Future Directions

UHPC-specific bond–slip laws. Existing interface models are largely calibrated on normal or high-strength concrete; there is no widely validated bond–slip law tailored to UHPC matrices that captures its dense microstructure, fiber bridging, and distinct post-cracking behavior.

- 1) Quantified roughness–performance mapping. Surface preparation is still reported by method labels (grinding, sandblasting, grooving) rather than standardized 3D roughness metrics. A reproducible mapping from parameters (e.g., Sa, Sz, Ssk, Sdr) to τ_{max} , slip at peak, and fracture energy is missing.
- 2) Optimum groove geometry for UHPC substrates. Design-ready limits for groove width/depth/spacing on UHPC are not established to balance mechanical interlock gains against cover weakening and stress hot-spots.
- 3) Adhesive selection and interfacial physics. The coupled roles of epoxy viscosity, glass-transition temperature (T_g), cure kinetics, and layer thickness on wet-out, surface energy, and early-age bond formation on low-permeability UHPC remain under-characterized.
- 4) Mixed-mode fracture characterization. Most studies emphasize Mode II (shear) via single-lap tests; robust Mode I/II (mixed-mode) protocols (e.g., DCB/ENF variants) and associated interfacial fracture energies for CFRP–UHPC are scarce.
- 5) Durability under realistic exposures. Long-term evolution of bond parameters under saline immersion vs. fresh water, thermal–moisture cycling, freeze–thaw, UV, and sustained load (creep) has not been systematically quantified for CFRP–UHPC interfaces.
- 6) Fatigue and service-life modeling. Data linking cyclic loading to interface degradation, failure-mode transitions, and residual bond–slip parameters over service lives typical of bridge or marine environments are limited.
- 7) From coupon to member scale. There is a weak, generalizable link between coupon-level interface parameters and beam-level flexural response (load, slip profiles, debonding patterns) for UHPC members strengthened with CFRP laminates.

Conclusion

Across EB-CFRP and UHPC–NC interfaces, the literature converges on a core message: surface preparation is the first-order lever for reliable bond behavior. Controlled roughness—achieved via calibrated sandblasting or proportioned grooving—raises peak interfacial shear stress, lengthens the effective anchorage zone, and delays adhesive debonding. Where substrates are compromised (e.g., heat-damaged concrete), transverse grooves and other mechanical keys can recover bond capacity when geometry is constrained to avoid cover weakening.

For UHPC-specific applications, dense matrix characteristics and distinct cracking micromechanics demand explicit measurement of roughness and pull-off strength, not just method labels. Adjusting a bond–slip law to the selected UHPC mix and adhesive system strengthens the connection between member-level performance and interface tests, informing lap length and clarifying decisions under design standards including ACI 440.2R and Leading gap is durability; future programs ought use salt and thermal- Track how environmental exposures, moisture cycles, and consistent roughness reporting help to define standards. reframe failure modes and τ –s factors across time.

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