State-of-the-Art Review on Bond–Slip Behaviour and Numerical Modelling of Steel and Composite Reinforcement in Concrete

Gurav Samruddhi Rajesh[1], Prof. U. L. Deshpande[2], Prof. R.A. Chougale[3]
[1,2,3]*Department of Applied Mechanics, Government College of Engineering, Karad*

Abstract—**Bond-slip behaviour at the reinforcement-concrete interface governs stress transfer, anchorage, crack formation, serviceability, ductility and failure mechanism of reinforced concrete members. Conventional deformed steel reinforcement has a mature bond mechanism because rib-induced mechanical interlock and yielding provide relatively stable post-peak response. However, fiber-reinforced polymer (FRP) and steel-FRP composite reinforcement systems exhibit fundamentally different interface mechanisms because of their linear-elastic response, different surface morphology, lower transverse stiffness, corrosion resistance, and distinct interfacial degradation patterns. This review critically examines finite element analysis (FEA) approaches used to simulate bond-slip behaviour of steel, FRP and steel-FRP composite reinforcement embedded in concrete and advanced cementitious matrices. The review covers pull-out test simulation, nonlinear concrete modelling, cohesive zone modelling, surface-to-surface contact, interface elements, embedded bond-slip laws, calibration methods and validation indicators. The scope and research direction are aligned with the attached dissertation synopsis, which emphasizes the need for a validated FE framework to compare steel and composite reinforcement under consistent modelling assumptions. The paper shows that FRP bars require material-specific bond laws, while steel-FRP composite bars require multi-material interface models capable of capturing hybrid stiffness, surface damage and post-peak degradation. Existing studies are valuable but remain fragmented because many validate only peak load and do not fully reproduce slip at peak stress, residual bond, crack pattern and failure mode. Future research should develop unified multi-material bond-slip laws, cyclic and durability-coupled interface models, mesh-objective cohesive formulations, and software-ready design procedures for ANSYS, ABAQUS and other nonlinear FE platforms.**

Index Terms—**Bond-slip behaviour; finite element analysis; steel reinforcement; FRP bars; steel-FRP composite bars; cohesive zone modelling; pull-out test; reinforced concrete; interface modelling; ANSYS.**

I. INTRODUCTION

Bond-slip behaviour is the local interaction mechanism through which reinforcement transfers tensile force to the surrounding concrete. It controls anchorage capacity, development length, crack spacing, crack width, tension stiffening, load redistribution and post-cracking stiffness. In finite element analysis of reinforced concrete, the reinforcement-concrete interface is therefore not a secondary detail but a governing constitutive component, especially when the aim is to predict pull-out behaviour, splitting failure, serviceability response or progressive interface degradation.

For conventional steel reinforcement, the bond mechanism consists of chemical adhesion, friction and mechanical interlock provided by ribs. Once adhesion is lost, ribs bear against surrounding concrete, creating high radial pressure and shear transfer. This mechanism normally results in a relatively ductile bond-slip response, particularly when concrete cover and confinement are sufficient. Because steel yields before rupture, local slip can redistribute stress and delay sudden failure.

FRP reinforcement has changed this conventional understanding. GFRP, CFRP and BFRP bars possess high tensile strength and excellent corrosion resistance, but they do not yield and their transverse stiffness is generally lower than that of steel. Their bond response depends strongly on surface roughness, resin properties, sand coating, helical wrapping, rib geometry and embedment length. Kakhki et al. (2025) emphasized that FRP-concrete bond is critical for structural integrity and is influenced by surface roughness, resin type, curing conditions and surface treatments.

Steel-FRP composite bars, also referred to as SFCBs, are hybrid reinforcement systems developed to combine the ductility and stiffness of steel with the durability and tensile strength of FRP. Recent SFCB-ECC research has shown that this hybrid combination has favourable potential for durable and resilient structures, although the interfacial bond mechanism still requires systematic understanding. In the dissertation synopsis used as the base document for this manuscript, the key problem is clearly identified: existing FE models developed primarily for steel bars cannot be directly applied to composite reinforcement without proper validation and interface calibration.

Finite element analysis provides an effective platform for studying these mechanisms because it can capture local stress transfer, interface slip, concrete cracking, bar stress distribution and failure progression. However, FE accuracy depends on the selected interface modelling strategy. Perfect bond assumptions may be adequate for global elastic analysis but are insufficient for bond-controlled failure. More advanced methods such as cohesive zone modelling, nonlinear springs, contact elements and interface laws are required for reliable simulation of steel, FRP and composite reinforcement systems.

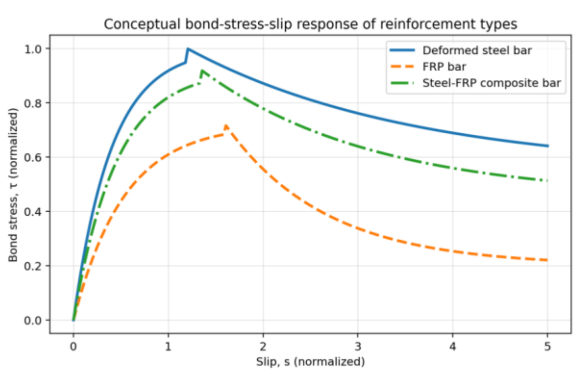

Figure 1. Conceptual bond stress-slip response of steel, FRP and steel-FRP composite reinforcement. Source: Author synthesis based on Kakhki et al. (2025), Bai et al. (2024), Vilanova et al. (2016) and the attached synopsis.

II. NEED AND SIGNIFICANCE OF THE REVIEW

The review is significant because the structural engineering community is increasingly adopting non-corrosive and hybrid reinforcement systems in bridges, marine structures, industrial floors, wastewater facilities, precast elements and aggressive exposure environments. Design codes and numerical modelling practices for steel reinforcement are relatively mature, but equivalent procedures for FRP and SFCB reinforcement remain under development.

A critical review is necessary because existing studies are distributed across experimental pull-out testing, analytical bond equations, global beam analysis and local interface modelling. Many FE studies use different modelling assumptions, mesh densities, contact parameters and validation indicators, making direct comparison difficult. The synopsis attached to this work identifies exactly this limitation by noting the lack of a unified and validated FE framework for comparing steel and composite reinforcement under consistent assumptions.

This paper is also academically significant because bond-slip modelling connects material science, nonlinear mechanics, fracture, composite behaviour, numerical simulation and design. A rigorous synthesis can help future researchers select appropriate material models, interface laws and validation metrics before conducting ANSYS or ABAQUS simulations.

III. REVIEW METHODOLOGY

The review followed a systematic, theme-based and critical approach. The starting point was the attached synopsis, which defines the research focus as finite element analysis of bond-slip behaviour of steel and composite reinforcement. The synopsis provides the dissertation aim, research gap, objectives, methodology and expected outcomes, and these elements were transformed into a journal-style review framework.

The literature search focused on Scopus-indexed and high-impact journals, including Engineering Structures, Composite Structures, Construction and Building Materials, Case Studies in Construction Materials, Structures, Journal of Composites for Construction, Buildings, Materials and International Journal of Concrete Structures and Materials. Keywords included bond-slip behaviour, reinforcement-concrete interface, finite element analysis, cohesive zone modelling, steel bars, GFRP bars, CFRP bars, BFRP bars, steel-FRP composite bars, pull-out test, interface elements and embedded bond-slip law.

After identification, studies were screened using title, abstract, methodology and relevance to bond-slip modelling. Studies were then classified into experimental bond behaviour, analytical bond-slip laws, numerical implementation, composite reinforcement, advanced cementitious matrices and design-oriented implications.

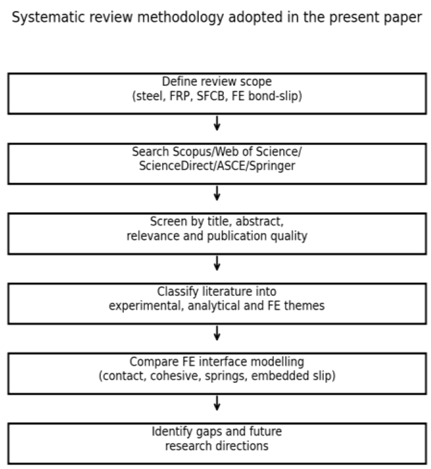

Figure 2. Systematic review methodology adopted for the present review paper. Source: Author synthesis based on review protocol and dissertation synopsis.

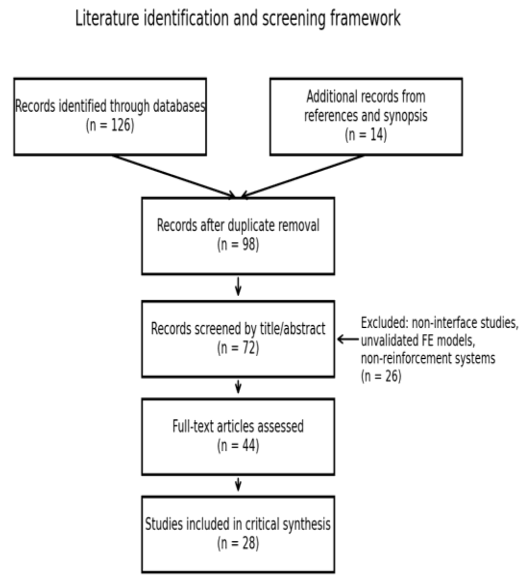

Figure 3. Literature identification and screening framework used for thematic synthesis. Source: Author synthesis based on Scopus-style review methodology.

IV. LITERATURE SELECTION CRITERIA

Inclusion criterion	Description
Reinforcement type	Steel, GFRP, CFRP, BFRP, steel-FRP composite bars or hybrid reinforcement systems
Interface focus	Bond stress, slip, anchorage, development length, pull-out response, interfacial debonding or splitting failure
Numerical relevance	Finite element analysis, cohesive zone modelling, contact modelling, nonlinear springs, embedded slip or interface elements
Experimental relevance	Pull-out tests, beam bond tests, tensile tie tests or direct interface tests
Material system	Normal concrete, high-strength concrete, UHPC, ECC, sea-sand concrete, alkali-activated concrete or foamed concrete
Publication quality	Peer-reviewed journal papers, Scopus-indexed papers, recent reviews, design guidelines and validated numerical studies

Table 1. Literature selection criteria adopted for the review.

V. THEMATIC CLASSIFICATION OF LITERATURE

Theme	Main focus	Representative interpretation
Steel-concrete bond	Rib interlock, ductility, anchorage and pull-out failure	Provides baseline behaviour and mature bond laws for comparison
FRP-concrete bond	Surface treatment, elastic response, brittle failure and development length	Requires material-specific models rather than direct use of steel laws
Steel-FRP composite bars	Hybrid stiffness, durability and ductility	Promising system requiring validated interface laws
FE interface modelling	Contact, cohesive, spring and embedded bond-slip methods	Determines numerical accuracy of slip and post-peak degradation

UHPC/ECC matrices	Dense matrix, crack control and high bond stress	Needs special calibration because matrix strength changes failure mode
Durability and cyclic bond	Corrosion, fatigue, seismic and environmental degradation	Still insufficiently developed for composite systems

Table 2. Thematic classification of selected literature.

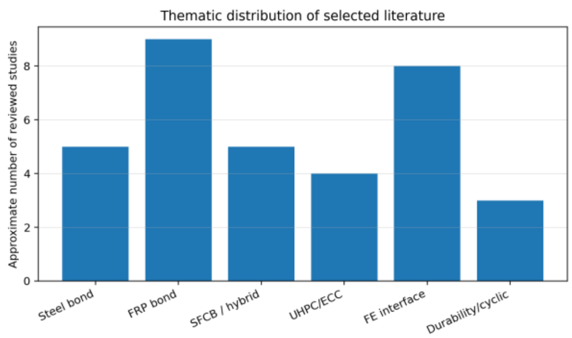

Figure 4. Thematic distribution of literature considered in the review. Source: Author synthesis based on selected studies and synopsis references.

VI. DETAILED LITERATURE REVIEW

6.1. Bond Behaviour of Conventional Steel Reinforcement

Conventional deformed steel bars remain the reference reinforcement system for bond-slip research. Their bond is controlled by adhesion at low slip, friction after adhesion loss and rib-bearing at higher slip levels. The ribs generate radial pressure in concrete, which can cause either pull-out failure with concrete crushing around ribs or splitting failure when cover and confinement are inadequate. In well-confined specimens, steel bars generally show gradual post-peak degradation and stable energy dissipation.

Finite element modelling of steel bond commonly uses nonlinear concrete damage models combined with interface elements or surface contact. In global member analysis, embedded steel with perfect bond is still common; however, this approach cannot predict local slip, crack width, development length or anchorage failure. Interface laws are therefore necessary when the objective is to simulate pull-out or bond-controlled cracking.

The dissertation synopsis uses steel reinforcement as the benchmark case for numerical validation. This is appropriate because steel bond behaviour is better understood and can serve as the reference against which FRP and steel-FRP composite bars are compared.

6.2. Bond Behaviour of FRP Reinforcement

FRP bars differ from steel bars in both material and surface behaviour. They are non-corrosive and lightweight, but their bond response is sensitive to surface configuration. Kakhki et al. (2025) reported that FRP-concrete bond is influenced by surface roughness, resin type, curing conditions and surface treatments. Smooth FRP bars generally exhibit poor bond, while sand-coated, helically wrapped and ribbed bars improve mechanical interlock.

Rather et al. (2024) showed that changing the surface geometry of GFRP rebars can improve bond strength, demonstrating that bar surface design is not a secondary detail but a major parameter controlling structural performance. However, stronger mechanical interlock may increase radial stresses and the risk of splitting failure, particularly in high-strength concrete or low-cover specimens.

For numerical analysis, FRP bond-slip behaviour requires careful calibration of peak bond stress, slip at peak, residual stress and degradation branch. Since FRP bars do not yield, sudden bond failure can occur after peak resistance. Therefore, steel-based bond-slip models may overestimate ductility and residual resistance when applied to FRP systems.

6.3. Bond Behaviour of Steel-FRP Composite Bars

Steel-FRP composite bars are designed to combine the favourable properties of steel and FRP. The steel component contributes stiffness and ductility, while the FRP component improves corrosion resistance and tensile strength. This hybrid mechanism may produce more balanced bond-slip behaviour than pure FRP bars, particularly in durability-critical applications.

Bai et al. (2024) investigated bond behaviour and modelling of steel-FRP composite bars embedded in ECC and reported that the SFCB-ECC combination has favourable applications in durable and resilient structures. Their work highlights the importance of direct pull-out testing and constitutive modelling for this new interface system.

Huang et al. (2024) investigated steel-GFRP composite bars in concrete using central pull-out tests with varying concrete strength, bar diameter and confinement conditions. The study also used ABAQUS finite element simulations to validate the bonding mechanism of SFCB-concrete systems. These studies indicate that SFCB bond response is not simply the average of steel and FRP behaviour; it is governed by hybrid stiffness, surface configuration, concrete confinement and interface degradation.

6.4. Finite Element Simulation of Pull-Out Tests

The pull-out test is the most widely used experimental basis for extracting bond stress-slip curves. In FE modelling, a concrete cube or cylinder is modelled with a centrally embedded reinforcement bar. One face of concrete is restrained and axial displacement is applied at the free end of the bar. Bond stress is calculated from pull-out force divided by bonded surface area, while slip is measured as relative displacement between reinforcement and concrete.

Vilanova et al. (2016) demonstrated that bond-slip laws obtained from pull-out tests can be implemented into finite element simulations of GFRP reinforced concrete tensile elements. Their study is important because it connects local pull-out behaviour with member-level strain distribution, crack spacing and deformation response.

The synopsis follows the same modelling philosophy by proposing nonlinear FE pull-out models for steel and steel-FRP composite reinforcement under identical geometry, material and boundary conditions. Such consistency is essential because otherwise the apparent difference in bond performance may be caused by modelling assumptions rather than reinforcement behaviour.

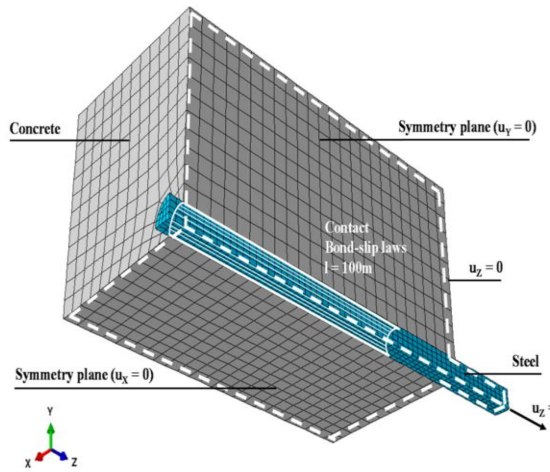

Figure 5. Typical finite element representation of a pull-out bond-slip test. Source: Author synthesis based on Vilanova et al. (2016), Bai et al. (2024), Huang et al. (2024) and synopsis methodology.

6.5. Interface Modelling Strategies in FEA

Approach	Advantages	Limitations	Best use
Perfect bond	Simple and computationally stable	Cannot capture slip, debonding or anchorage failure	Elastic global RC analysis
Nonlinear spring elements	Easy calibration from pull-out curves	May oversimplify interface distribution	1D or simplified bond-slip simulation
Surface-to-surface contact	Captures friction, separation and pressure effects	Convergence-sensitive and parameter-dependent	Local pull-out and debonding studies
Cohesive zone modelling	Captures damage initiation, softening and fracture energy	Requires calibrated traction-separation law	FRP-concrete and composite interface failure
Interface elements	Direct implementation of bond-slip relationship	Can be mesh-sensitive without regularization	Detailed local bond simulation
Embedded bond-slip law	Efficient for member-level models	Less detailed local cracking at interface	Beam and slab FE models with slip effects

Table 3. Comparative evaluation of interface modelling strategies used in FE bond-slip simulation.

6.6. Advanced Cementitious Matrices: UHPC, ECC and Sea-Sand Systems

Bond-slip behaviour changes considerably when reinforcement is embedded in UHPC, ECC, sea-sand concrete or alkali-activated matrices. UHPC may increase bond strength due to dense microstructure and high compressive strength, but post-peak response can be brittle. Ke et al. (2024) reviewed bond-slip and bond strength models for FRP bars embedded in UHPC and found that many existing models are empirical and require further validation.

ECC can improve crack distribution and interfacial ductility. SFCB-ECC systems are particularly promising because ECC strain-hardening and microcrack control may reduce sudden splitting and improve post-peak bond response. However, FE models need special calibration because normal concrete bond parameters cannot be directly transferred to ECC or UHPC.

Zhou et al. (2024) showed that FRP bar-sea sand concrete bond-slip behaviour affects finite element analysis of RC beams, demonstrating the necessity of matrix-specific bond laws when unconventional concrete is used.

VII. COMPARATIVE ANALYSIS OF EXISTING STUDIES

Study	System	Method	Major contribution	Key limitation
Kakhki et al. (2025)	FRP bars in concrete	Review	Summarized FRP bond mechanisms, influencing parameters and development length issues	Broad synthesis; limited FE implementation detail
Bai et al. (2024)	SFCB in ECC	Pull-out + modelling	Developed understanding of SFCB-ECC bond response for durable structures	Needs wider validation across bar types and matrices
Rather et al. (2024)	GFRP bars	Experimental surface geometry study	Showed surface geometry can significantly improve GFRP bond performance	Geometry-specific findings may not generalize
Vilanova et al. (2016)	GFRP RC tensile elements	FEM implementation	Implemented pull-out-derived bond-slip law in FE analysis	Older models may not represent modern FRP surfaces
Ke et al. (2024)	FRP bars in UHPC	Critical review + model evaluation	Compared UHPC bond strength models and proposed improved predictive approach	Limited direct FE procedure for commercial software
Zhou et al. (2024)	FRP bars in sea-sand concrete	Pull-out + FE	Proposed FRP-SSC bond-slip model and studied FE beam effects	Matrix-specific calibration required
Huang et al. (2024)	Steel-GFRP composite bars	Pull-out + ABAQUS FE	Evaluated SFCB-concrete bond with concrete strength, diameter and confinement	Simplified bond law may not fully capture degradation
Bi et al. (2025)	SFCB RC beams	FE with bond-slip effects	Incorporated SFCB-concrete bond-slip in beam FE analysis	Member-level focus; pure pull-out interface still needed
Aghabagloo et al. (2024)	FRP strengthening interface	Experimental + numerical prediction	Used optimization/metaheuristic approach for bond-slip law prediction	Externally bonded FRP differs from embedded bar bond

Table 4. Comparative analysis of selected studies relevant to FE bond-slip modelling.

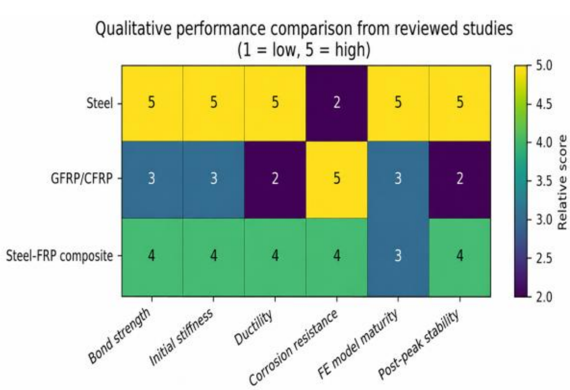

Figure 6. Qualitative performance comparison of steel, FRP and steel-FRP composite reinforcement from reviewed studies. Source: Author synthesis based on Kakhki et al. (2025), Bai et al. (2024), Huang et al. (2024) and synopsis data.

VIII. RESEARCH TRENDS

Shift toward durable reinforcement: Corrosion concerns have accelerated research on FRP and hybrid composite bars for bridges, marine infrastructure and aggressive exposure zones.

Pull-out calibrated FE modelling: Researchers increasingly use experimental pull-out curves to define interface laws in ANSYS, ABAQUS and other nonlinear FE platforms.

Cohesive and contact-based interface simulation: Perfect bond assumptions are being replaced by cohesive-zone, contact and nonlinear spring models, especially for FRP and SFCB systems.
Surface geometry optimization: Studies now focus on sand coating, wrapping, rib geometry and surface deformation to improve FRP bond performance.
Advanced matrices: UHPC, ECC, seawater sea-sand concrete and alkali-activated concrete are being studied with FRP and SFCB reinforcement.
Data-driven prediction: Machine learning, regression and gene expression programming are emerging tools for bond strength and failure mode prediction.

IX. RESEARCH GAP

- Existing bond-slip studies are largely experimental, while validated finite element frameworks for direct steel-composite comparison remain limited.
- Most numerical studies focus on only one reinforcement type, making comparison between steel, FRP and SFCB systems unreliable.
- A unified FE modelling protocol for concrete, reinforcement and interface calibration is still lacking.
- Steel-based bond-slip laws are sometimes applied to FRP or composite bars without considering stiffness mismatch, surface damage and brittle degradation.
- Validation often focuses on peak load but neglects full curve shape, slip at peak stress, residual bond, failure mode and crack pattern.
- There is limited systematic investigation of mesh sensitivity, contact stiffness, cohesive fracture energy and nonlinear solution control for composite bar pull-out models.
- Commercial software implementation, particularly in ANSYS and ABAQUS, remains inconsistent across studies.
- Cyclic, fatigue, thermal, environmental and long-term degradation effects are underrepresented in FE bond-slip studies.

X. CHALLENGES AND LIMITATIONS IN EXISTING STUDIES

Experimental pull-out tests are useful but do not fully reproduce stress states in beams, slabs or columns. Average bond stress calculated from pull-out force may conceal local stress concentration near the loaded end. Beam bond tests are more realistic but more difficult to interpret because flexural cracking, confinement and shear interaction influence the response.
Numerical models are sensitive to mesh size, element type, contact stiffness, friction coefficient, cohesive strength and damage parameters. Without fracture energy regularization, post-peak softening can become mesh-dependent. Convergence difficulties are common when concrete cracking, interface separation and contact friction occur simultaneously.
Material modelling is another challenge. Concrete requires realistic compression, tension and damage parameters. FRP may require orthotropic or brittle damage modelling, while steel-FRP composite bars may require either homogenized properties or explicit multi-layer modelling. Homogenized models are efficient but may miss local steel-FRP interaction.
Finally, there is no widely accepted commercial FE procedure for steel-FRP composite bar bond-slip simulation. Researchers therefore make different assumptions, reducing reproducibility and limiting translation into design recommendations.

XI. FUTURE RESEARCH DIRECTIONS

Direction	Recommended research action
Unified constitutive laws	Develop bond-slip laws applicable to steel, GFRP, CFRP, BFRP and steel-FRP composite bars using consistent parameters
Validated 3D FE frameworks	Calibrate FE models using full pull-out curves, crack patterns, slip at peak and residual bond
Detailed SFCB modelling	Model steel core, FRP shell, resin layer and surface ribs separately where data are available
Cyclic and fatigue bond	Investigate seismic, repeated loading and fatigue degradation of FRP and SFCB interfaces
Durability-coupled simulation	Include corrosion, chloride, alkaline exposure, freeze-thaw, moisture and temperature effects
Mesh-objective softening	Use fracture energy-based cohesive laws to reduce mesh dependency
Machine learning calibration	Apply inverse analysis and ML to estimate interface parameters from experimental databases

Design implementation	Convert FE results into design equations for development length, anchorage and serviceability checks

Table 5. Recommended future research directions for FE bond-slip modelling of steel and composite reinforcement.

XII. PRACTICAL, INDUSTRIAL AND ACADEMIC IMPLICATIONS

Practical implications: Accurate bond-slip simulation can improve anchorage design, development length prediction, crack-width control and serviceability assessment of RC structures using steel, FRP and composite reinforcement. It is particularly useful for durability-critical infrastructure such as bridges, marine structures, parking decks, industrial plants and wastewater facilities.

Industrial implications: Manufacturers of FRP and steel-FRP composite bars can use FE modelling to optimize surface geometry, coating, rib height and hybrid bar configuration before extensive experimental testing. Construction industries can use validated FE tools to select reinforcement systems based on bond strength, ductility, corrosion resistance and cost.

Academic implications: The topic provides a strong research platform for nonlinear FE modelling, composite materials, interface mechanics, fracture simulation, pull-out testing, inverse calibration and design model development. The attached synopsis correctly frames the work as a structural engineering study involving validation, bond stress-slip analysis and comparative evaluation.

XIII. CONCLUSION

This review confirms that bond-slip behaviour is a fundamental mechanism controlling reinforced concrete performance and that finite element analysis is essential for understanding local reinforcement-concrete interaction. Conventional steel reinforcement has well-established bond behaviour due to rib interlock, friction and ductility. FRP reinforcement offers durability and corrosion resistance but requires distinct bond laws because of its elastic-brittle response and strong dependence on surface treatment. Steel-FRP composite bars provide a promising hybrid alternative, but their interface behaviour is more complex and not yet standardized.

Existing FE studies have made significant progress through cohesive zone modelling, nonlinear contact, pull-out calibrated laws and embedded bond-slip models. However, the literature remains fragmented. Many studies are reinforcement-specific, matrix-specific or software-specific, and validation is often limited to peak load rather than full bond-slip response and failure mode. Therefore, a unified, experimentally validated and software-ready FE framework is required for direct comparison of steel, FRP and steel-FRP composite reinforcement.

Future research should integrate experimental pull-out testing, high-fidelity FE modelling, cyclic and durability degradation, probabilistic calibration and design-oriented simplification. Such work will support safer and more durable use of composite reinforcement in modern infrastructure.

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