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Research Progress and Outlook on Rebar Anchoring Technology

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Abstract

As a core form of post-installed anchoring technology, rebar planting has been widely applied in engineering fields such as the reinforcement of existing structures, the connection of new and existing structures, and the construction of new structural joints, thanks to its advantages of construction flexibility, reliable anchoring, and strong adaptability.In recent years, with the expansion of engineering applications and the emergence of new structural materials, the scope of research on rebar anchoring technology has gradually extended from traditional concrete substrates to new materials such as engineered bamboo, ultra-high-performance concrete, and 3D-printed concrete. The research focus has deepened from the basic performance of individual rebars to the mechanical properties of structural members, the seismic performance of structural systems, and long-term service performance.Based on the findings of relevant domestic theses from 2021 to 2025, this paper focuses on two major areas—the anchoring performance of rebar in concrete substrates and the anchoring performance of rebar in bamboo and wood structures—systematically reviews research progress in areas such as interfacial bonding mechanisms, performance evolution under complex environmental conditions, stress characteristics of special construction details, and the mechanical properties of components and structural systems. It summarizes the current characteristics and shortcomings of the research and outlines future research directions, with the aim of providing a reference for further research and engineering applications of rebar anchoring technology.

Keywords

Rebar anchoring,bond performance, interfacial shear strength, service environment, bamboo and wood structures, research progress.

1. Introduction

Post-installed rebar anchoring technology bonds reinforcing bars to the substrate into an integrated unit using adhesives to achieve load transfer and structural connection. It combines the advantages of convenient construction, flexible layout, and high anchoring efficiency, making it one of the most widely applied technologies in the field of structural reinforcement and retrofitting in civil engineering.Early research and applications of rebar post-installation technology primarily centered on concrete substrates, focusing on the pull-out performance of single rebars, the mechanisms of bond slip, and basic design methods, thereby establishing a relatively mature theoretical framework.As China’s infrastructure development enters a phase characterized by both the renewal of existing assets and the improvement of new projects, engineering scenarios such as the raising of water conservancy dams, high-speed rail track repairs, and underground space development have placed higher demands on rebar anchoring technology. At the same time, the widespread adoption of new structural materials—such as bamboo, ultra-high-performance concrete (UHPC), and 3D-printed concrete—has also driven the continuous expansion of the research scope for rebar anchoring technology.

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In recent years, domestic scholars have conducted extensive experimental and theoretical research on the anchoring performance of embedded bars under different matrix materials, operating conditions, and scales, achieving rich interim results.This paper systematically reviews the research content of 20 recent domestic theses. Focusing on two major dimensions—the anchoring performance of rebar in concrete substrates and that in bamboo and wood structures—it summarizes research progress in areas such as interfacial shear resistance, response to complex service environments, anchoring characteristics in special structural configurations, and the mechanical properties of components and systems. The paper analyzes the common features and existing shortcomings of current research and outlines future research directions.

2. Research on the Anchoring Performance of Rebar Embedment in Concrete Substrates

Concrete is the most fundamental substrate for rebar anchoring technology. Related research covers multiple aspects, including the mechanisms of force transfer at the interface, the evolution of environmental performance, the design of special structures, and the mechanical response of members, thereby forming the core theoretical foundation of rebar anchoring technology.

2.1. Shear Resistance at the Interface Between New and Old Concrete

The interface between new and old concrete is a weak point in structural reinforcement and expansion projects, and rebar anchoring is a core technical method for improving the shear resistance of this interface and enhancing the structural integrity. Researchers have conducted targeted experimental and theoretical studies on various interface configurations encountered in different engineering scenarios.

Addressing the inclined bond surfaces commonly found in concrete gravity dam raising projects, Yang Chen[1] employed a combined approach of oblique shear tests and numerical simulation to systematically investigate the effects of rebar arrangement, rebar ratio, and rebar depth on the oblique shear performance of the bond surface between new and old concrete. The study found that rebar insertion can effectively alter the failure mode of test specimens, transforming the brittle failure of unreinforced specimens into ductile failure;the oblique shear strength increased to varying degrees with increases in the reinforcement ratio and embedment depth, with the inverted triangular arrangement providing the optimal reinforcement effect, followed by the vertical arrangement, the equilateral triangular arrangement, and the horizontal arrangement. Based on these findings, the study combined shear friction theory with the calculation formula for the load-bearing capacity of oblique cross-sections to establish a computational model for the oblique shear bond strength between new and old concrete using embedded bars, providing a theoretical basis for the shear design of inclined interfaces.

For the composite interface where UHPC reinforces ordinary concrete, Xian Xuelai[2] conducted experiments using “Z”-shaped direct shear specimens to investigate the influence of rebar diameter, rebar ratio, and anchorage depth on the shear performance of the UHPC-NC interface.The study indicates that embedded bars can significantly enhance the ultimate shear capacity and stiffness of the composite interface. The stress distribution in the shear reinforcement at the interface exhibits non-uniform characteristics, with maximum stress occurring near the interface and gradually decreasing along the embedment depth. Finite element simulation results show that the maximum stress in the specimens is consistently concentrated in the interface region, consistent with the experimental failure patterns. This

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study further analyzes the shear force transfer mechanism at the interface, providing experimental evidence for the design of interface connections in UHPC reinforcement projects.

Overall, current research on shear reinforcement at interfaces between new and old concrete has covered both conventional flat and inclined interfaces, and corresponding load-bearing capacity calculation methods have been established; however, systematic parametric studies addressing different interface inclination angles and concrete strength combinations still require further refinement.

2.2. Evolution of Bond Performance under Complex Service Conditions.

During service, rebar-embedded anchorage structures are inevitably subjected to environmental factors such as temperature, freeze-thaw cycles, and long-term loads, causing the bond performance at the interface to degrade to varying degrees, which in turn affects the structural safety and durability. In recent years, the evolution patterns of rebar-concrete bond performance under complex service conditions have become a research hotspot.

Temperature is a key factor affecting the bond performance of rebar-in-concrete systems. Ling Yuand conducted systematic studies on the effects of temperature on the bond-slip behavior at the adhesive-rebar and adhesive-concrete interfaces, using steel-sleeve rebar-in-concrete specimens and concrete rebar-in-concrete specimens, respectively. Through static pull-out tests under different temperature conditions, they fitted the dual-interface bond -slip constitutive relationship that accounts for temperature effects; combined with ABAQUS finite element simulations, the distribution of bond stress along the embedment depth was analyzed, and the position function of the bond-slip constitutive relationship was obtained through regression. Ultimately, a bond-slip constitutive relationship for rebar anchoring across the full embedment depth that accounts for temperature effects was established, providing a constitutive foundation for the performance analysis of rebar-anchored structures in high-temperature environments. Huang Zipeng Focusing on the repair scenario of CRTS II ballastless track using rebar anchoring, high- and low-temperature cyclic tests on concrete–mortar composite specimens verified that rebar anchoring can significantly enhance the shear and splitting performance at the interface between the track slab and the CA mortar layer. Furthermore, a refined finite element model was established based on field-measured temperature data, revealing the evolution of the mechanical behavior of the repaired interface under temperature loading.

Freeze-thaw cycles pose a major service challenge for rebar-embedded structures in severely cold northern regions. Li Shiqi[5] conducted a comparative study of the interface bond performance under different numbers of freeze-thaw cycles for two anchoring systems: rebar installation followed by freeze-thaw cycles and freeze-thaw cycles followed by rebar installation. The test results indicate that the interface bond performance of specimens subjected to freeze-thaw cycles followed by rebar installation was generally superior to that of specimens subjected to rebar installation followed by freeze-thaw cycles;As the number of freeze-thaw cycles increased, the failure mode gradually shifted from failure at the rebar-adhesive interface to failure at the adhesive-concrete interface. This study derived the bond-slip constitutive equations for the rebar-concrete interface under different freeze-thaw cycle counts and calculated the basic bonded anchorage length under corresponding freeze-thaw conditions based on the freeze resistance coefficient, providing a reference for the design of rebar-embedded structures in freeze-thaw zones.

Creep deformation under long-term loading is a critical factor affecting the long-term service performance of rebar-embedded structures. Liang Decai[6] conducted creep tests on rebar-embedded systems under 90-day long-term loading, systematically analyzed the influence of parameters such as stress level, rebar diameter, concrete strength, and embedment depth on creep deformation, and determined the development patterns and convergence trends of creep

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strain over time under sustained loading.The study further evaluated the residual load-bearing capacity and seismic anchoring performance of the rebar-in-concrete system after long-term loading through unloading pull-out tests and cyclic loading tests. It proposed a reduction factor for bond strength under long-term loading and a method for predicting rebar slippage over a 50-year period, providing a theoretical basis for the full life-cycle performance assessment of rebar-in-concrete structures.

Existing research has clarified the influence of single factors—such as temperature, freeze-thaw cycles, and long-term loading—on the bond performance of rebar-embedded structures; however, in actual engineering applications, these structures often experience the coupled effects of multiple factors, and the relevant mechanisms of such coupling and performance evolution models still require in-depth study.

2.3. Anchoring Performance under Special Structures and Adverse Conditions

In actual engineering projects, special configurations and adverse conditions—such as curved substrates, concrete cracking, small edge distances, and multi-bar anchorage—often occur. Conventional design theories for planar single-bar rebar anchoring are difficult to apply directly; relevant research has gradually filled the gaps in this field.

In response to the need for curved-surface rebar anchoring in “pile-wall integrated” structures for underground engineering, Zhuo Zhiquan and Fang Ruiying conducted systematic theoretical and numerical research. Zhuo Zhiquan[7] established theoretical models for the anchoring of single and multiple rebars on curved surfaces and derived corresponding ultimate load-bearing capacity formulas; numerical verification showed that the calculated results from the formulas agreed well with the simulation values;Parametric analysis revealed that the ultimate load-bearing capacity of a single rebar increases with increases in the surface radius, rebar embedment depth, and adhesive thickness, while the ultimate load-bearing capacity of multiple rebars increases with an increase in the rebar embedment angle; the load-bearing capacity of a single rebar can be fully utilized when the rebar spacing is 300 mm.Fang Ruiying[8] further applied curved-surface rebar anchoring technology to an integrated tunnel pull-groove pile–slab wall structure. Through finite element analysis under all operating conditions, she verified the advantages of this structure over traditional support structures in terms of load-bearing performance, buoyancy resistance, and temperature adaptability, providing practical guidance for the engineering application of curved-surface rebar anchoring.

Addressing the common issues of concrete cracking and small edge distances in the reinforcement of existing structures, Liu Rui[9] conducted pull-out tests on rebar embedded in cracked concrete and under small edge distance conditions, respectively. The study showed that an increase in crack width has a significant negative impact on the bond performance of the embedded rebar, and that the failure mechanisms and patterns of bond performance changes under small edge distance conditions differ markedly from those under unconstrained conditions.Based on the experimental results, this study proposed ultimate load-bearing capacity formulas for unconstrained and constrained rebar pull-out under small edge-to-edge distance conditions, with calculation errors controlled within ±15%. It also pointed out that the splitting influence factor specified in current codes is unreasonable and that there is a lack of detailed provisions for rebar installation under small edge-to-edge distance conditions; accordingly, corresponding design improvement recommendations were proposed.

Han Zi’ang[10] Through large-sample constrained pull-out tests, this study systematically compared the differences in anchoring performance between post-installed rebars and embedded rebars.The study found that the variation patterns of bond strength for post-installed and embedded reinforcing bars are highly correlated, with the bond strength of post-installed bars being 1.1 to 2.4 times that of embedded bars. This validates the feasibility of the approach in European codes, whereby post-installed bars meeting performance requirements can be designed by reference to embedded bars. Additionally, the study offers design recommendations regarding the determination of interface bond strength values and structural requirements for post-installed bars.

To address non-ideal construction conditions such as dampness and dust, Liu Ran[11] developed a new type of inorganic rebar-in-concrete adhesive, and experiments verified that it maintains excellent bond and anchorage performance even under complex installation conditions.Research has found that the impact of complex installation conditions is most significant when the anchorage depth is shallow, and this impact gradually diminishes as the anchorage depth increases; based on the test results, a formula for calculating the load-bearing capacity of rebar anchoring under complex installation conditions was derived. Engineering verification indicates that the calculated values from the formula are slightly lower than the test values, providing a reasonable safety margin.

The group anchoring effect of multiple rebars is a key consideration in engineering design. Li Gang conducted systematic analyses of the influence of rebar spacing, edge distance, number, and embedment depth on the group anchoring effect through multiple-rebar pull-out tests and finite element simulations. The results indicate that the group anchoring effect decreases as rebar spacing and edge distance increase, but increases as the number of rebars increases;when the embedment depth is within the range of 6d to 10d, the cluster anchorage effect gradually weakens as the embedment depth increases, and the effect tends to stabilize when the embedment depth exceeds 10d. Based on the experimental and simulation results, this study derived a formula for calculating the load-bearing capacity of multi-bar rebar anchorage that accounts for the influence coefficients of spacing and edge distance; the calculated values agree well with the experimental data.

2.4. Mechanical Properties of Concrete Members with Embedded Rebars

Single-bar pull-out tests struggle to reflect the stress state of embedded bars in actual members. In recent years, researchers have progressively shifted their focus to studying the anchoring performance of embedded bars at the member scale to refine design theories at the member level.

Jia Yunfei[13] Through flexural loading tests on concrete beams with embedded bars, it was determined that the minimum anchorage depth for plastic failure in beams with two embedded bars is 25d; when the anchorage depth is less than 20d, the beam is prone to brittle pull-out failure;The study indicates that the interface between new and old concrete and the cross-section at the rebar tip are the weak points of rebar-reinforced beams. When the rebar tip is located in the flexural-shear zone, additional shear stress is generated, which can easily lead to oblique flexural-shear cracks.Finite element analysis indicates that when the anchorage spacing exceeds 6d, the overlap of stress zones among the embedded bars essentially disappears. Based on this, a threshold anchorage spacing of 6d is proposed at which the cluster anchorage effect can be neglected, and corrected formulas for anchorage depth and beam shear capacity—accounting for the influence of anchorage spacing—were established.

Zhou Xun[14] The application of rebar-in-concrete technology to 3D-printed concrete members has resolved the difficulty of reinforcing bars in the printing process.Pull-out test results indicate that high-flow rebar-embedding adhesive can effectively compensate for interlayer defects in printed concrete; the ultimate load and ductility of the rebar-embedded specimens were superior to those of traditional pre-embedded rebar specimens. When the bonded length reached 10 times the rebar diameter, the failure mode shifted from concrete splitting failure to rebar tensile failure.Shear tests on beams further verified that the embedded rebar technique can significantly enhance the shear capacity of 3D-printed concrete beams, providing a new approach to reinforcement design for 3D-printed concrete structures.

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3. Study on the Anchoring Performance of Rebar Planting in Bamboo and Wood Structures

With the promotion of green building concepts and the advancement of the "dual carbon" goals, biomass structural materials such as engineered bamboo and glued laminated timber have seen rapid development due to their advantages of being renewable and low-carbon. As a concealed, high-stiffness connection method, rebar planting has become an important technical approach for enhancing the performance of joints in bamboo and wood structures, and related research is gradually gaining momentum.

3.1. Bonding and Anchoring Performance of Rebar Embedment in Engineered Bamboo

Engineered bamboo exhibits significant anisotropy, with weaker mechanical properties in the cross-grain direction; the bonding and anchoring mechanism of rebar-embedded connections differs fundamentally from that in concrete substrates. Domestic scholars have conducted extensive pull-out tests on rebar-embedded connections in engineered bamboo using various processing methods.

Regarding side-pressed bamboo glulam, Xie Wanqiong and Liu Shuai conducted systematic studies on rebar anchoring performance in both the cross-grain and along-grain directions. Xie Wanqiong[15] Through 21 sets of single-bar rebar pull-out tests (totaling 126 specimens) conducted in the cross-grain direction, she analyzed the effects of edge distance, adhesive layer thickness, length-to-diameter ratio, and rebar type on pull-out capacity. She identified two primary failure modes—rebar pull-out failure and yield failure—and concluded that an edge distance of four times the rebar diameter can prevent splitting failure in bamboo, while 2 mm is the optimal adhesive layer thickness;A design formula for pull-out capacity was established based on reliability theory, and recommendations for joint design and construction were provided in conjunction with engineering case studies.Liu Shuai[16] Conducted tensile tests on reinforcing bars embedded along the grain of bamboo, identifying four failure modes, including bamboo splitting and bar pullout. The study similarly validated the rationality of a minimum edge distance of 4d and an optimal adhesive layer thickness of 2 mm. A bond-slip model for the embedded bar connection and an improved formula for pull-out capacity were established, and the finite element simulation results agreed well with the experimental data.

Yu Shaohua[17] Systematic tests were conducted on the self-developed inorganic adhesive-reinforced bamboo composite material, including transverse groove compression, rebar-reinforced local transverse groove compression, and rebar-reinforced transverse groove pull-out tests.The study determined the basic mechanical properties and standard strength values of this material under transverse compression, clarified the reinforcement mechanism of the number, diameter, and depth of embedded bars on the local transverse compressive performance, and proposed formulas for the load-bearing capacity of locally reinforced transverse compression and the pull-out capacity of embedded bars in transverse compression, respectively, providing a design basis for the engineering application of inorganic adhesive-reinforced bamboo.The magnesium-based inorganic binder used in this material effectively addresses the shortcoming of insufficient heat resistance in traditional organic adhesives, thereby enhancing the fire resistance of bamboo structures.

Zhang Han[18] A comparative study was conducted on the anchorage performance of two types of embedded reinforcement materials—steel bars and GFRP bars—in flattened bamboo glulam.The results show that the ultimate pull-out strength of both types of reinforcement increases with both the anchorage length and the diameter of the reinforcement. Specimens with steel reinforcement exhibited three failure modes: pull-out, yielding, and splitting, whereas specimens with GFRP reinforcement primarily failed by pull-out (accounting for 75%

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of cases); an increase in adhesive layer thickness had a slight enhancing effect on the bond performance of GFRP reinforcement.

Dai Shangqi[19] conducted experimental research on GFRP-reinforced bamboo-bonded joints, filling a research gap in GFRP-reinforced bamboo connections in engineering applications.The study found that shear failure at the Glubam–adhesive layer interface was the predominant failure mode, accounting for over 75% of cases; considering the comprehensive load-bearing capacity, stiffness, and ductility, 2 mm was determined to be the optimal adhesive layer thickness, and to prevent splitting failure, the edge distance ratio should not be less than 3.5; within the range of 0° to 90°, increasing the rebar insertion angle can enhance the joint's load-bearing capacity and ultimate slip, but it reduces the initial stiffness.

Overall, research on bamboo-reinforced anchorage has covered various bamboo species and rebar types, clarifying the influence patterns of key design parameters; however, existing studies have largely focused on the pull-out performance of single rebars, while research on the overall load-bearing performance and failure mechanisms of joints remains relatively insufficient.

3.2. Seismic Performance of Glulam Frames with Embedded Rebar

Building on studies of single rebars and joints, some researchers have further investigated the seismic performance of glued-laminated timber frames with embedded rebar connections at the structural system level. Sun Yuting[20] employed a multiscale finite element modeling approach to establish three types of glued-laminated timber frame models—pure embedded rebar connections, GFRP-rebar-reinforced, and GFRP-fabric-reinforced—and conducted modal analysis and static elastic-plastic analysis.The study indicates that both GFRP bars and GFRP fabric can effectively share the load carried by the embedded bars, significantly improving the frame's lateral stiffness and load-bearing capacity. Reducing the beam-to-column stiffness ratio and increasing the diameter of the embedded bars both enhance the frame's load-bearing capacity and lateral stiffness, whereas increasing the column axial compression ratio significantly reduces the frame's seismic performance.This study further explored the upper limit on the number of stories for frames with embedded-rebar connections, providing a theoretical reference for the engineering application of timber structures with embedded-rebar connections.

4. Summary and Outlook

4.1. Summary of Research Characteristics

Based on a synthesis of recent domestic research findings on rebar-embedded anchoring technology, three notable characteristics can be summarized:

First, the research methodology system is maturing. Mainstream research has generally established a closed-loop research paradigm of "experimental study—numerical simulation—theoretical modeling." Experimental methods cover various forms, including central pull-out, direct shear/oblique shear, and member loading, while finite element simulations have made significant breakthroughs in the refined characterization of interface bond-slip constitutive models. Theoretical research focuses on establishing load-bearing capacity calculation formulas and design methods, and the systematic nature and rigor of the research continue to improve.

Second, application scenarios and the scope of base materials continue to expand. Research subjects have gradually extended from the traditional reinforcement of concrete structures to specialized engineering fields such as the raising of hydraulic dams, high-speed rail track repair, and pile-wall connections in underground engineering; base material types have expanded from ordinary concrete to new cement-based materials such as UHPC and 3D-printed concrete,

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as well as biomass materials like engineered bamboo and glued laminated timber, continuously broadening the application boundaries of rebar planting technology.

Third, the scale and dimensions of research have continued to deepen. The research scale has gradually expanded from early-stage fundamental performance tests on individual rebars to meso- and macro-scales, such as the mechanical properties of structural members and the seismic performance of structural systems; the research dimensions have deepened from short-term static performance to long-term service performance—including temperature, freeze-thaw cycles, and long-term loading—gradually covering the performance requirements across the entire life cycle of structures.

4.2. Shortcomings and Outlook

Although research on rebar-embedding anchorage technology has yielded fruitful results, the following shortcomings remain to be addressed:

1. Insufficient research on multi-field coupled service environments. Existing studies primarily focus on single factors such as temperature, freeze-thaw cycles, and loads, whereas in actual engineering applications, rebar-embedded structures often endure the coupled effects of multiple factors. The mechanisms of interface damage and performance degradation models under such coupled conditions remain unclear, and there is an urgent need to conduct long-term performance tests and theoretical research on multi-field coupling.

2. The theoretical framework for new anisotropic matrix materials is incomplete. Biomass materials such as engineered bamboo and glued laminated timber exhibit significant anisotropic characteristics. Existing research has largely focused on macroscopic performance testing, and understanding of the microscopic bonding mechanisms at the rebar–adhesive–matrix interface and stress transfer mechanisms remains insufficient. Research at the joint and structural system levels is relatively scarce, and a systematic design methodology has yet to be established.

3. Design methods for clustered rebar anchors in complex spatial structures lack a systematic framework. Research on the clustered rebar anchor effects in complex structures—such as those with curved surfaces or irregular cross-sections—is still in its infancy. Existing findings are mostly tailored to specific engineering scenarios, and universal design theories and computational methods have yet to be established, making it difficult to meet the design requirements of complex engineering projects.

4. Research on full life-cycle performance evaluation lags behind. Existing long-term performance studies are mostly short-term accelerated tests, and there is a lack of long-term performance monitoring data under actual service conditions. Methods for reliability assessment and residual life prediction of rebar-embedded structures based on the full life cycle have yet to be established.

Future research could further explore the above directions to refine the theoretical framework of rebar-in-concrete anchoring technology, expand its scope of application, and provide technical support for the safe operation and sustainable development of civil engineering structures.

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