Proceedings of CONF-FMCE 2026 Symposium: Smart City and Infrastructure Engineering
DOI: 10.54254/2755-2721/2026.CH38169

Application and Durability of CFRP Composite Materials in Bridge Structures

Chenhao Zhao

School of Urban Construction, Yangtze University, Jingzhou, China
K00340330@student.tus.ie

Abstract. Carbon fiber reinforced polymers/plastics (CFRP) composites have the outstanding advantages of light weight, high strength, corrosion resistance, fatigue resistance, and so on, and have been widely used in bridge reinforcement and new bridge engineering. In this paper, the common engineering materials such as CFRP cloth, plate, reinforcement, cable, grid, and so on are reviewed, and their excellent mechanical properties are analyzed. At the same time, the inherent defects and typical damage forms, such as the weak transverse shear resistance of materials, the easy deterioration of resin in high-temperature environments, the potential for galvanic corrosion, and the high engineering cost, are analyzed. This paper compares the process characteristics and application conditions of three kinds of core engineering technologies, namely, externally bonded reinforcement, embedded reinforcement, and CFRP Cable bearing system, and summarizes the single working conditions of chloride, high temperature, and fatigue load, as well as the deterioration evolution law of the CFRP-concrete interface under the coupling effect of chloride, temperature change, fatigue, and freeze-thaw. From the aspects of material improvement, structural optimization, surface protection, and standardized construction, this paper summarizes the durability improvement technology, analyzes the existing problems in the industry, such as the short board of material performance, imperfect design specifications, and insufficient research on coupling environment, and puts forward development suggestions from the aspects of matrix modification, improving the standard system, carrying out long-term monitoring, and improving the full life cycle assessment, which can provide reference for the durability design and standardized application of CFRP composites in bridge engineering.

Keywords: CFRP composites, Bridge reinforcement, Prestressed CFRP, Interface bonding, Durability

1. Introduction

As a typical engineering case, Guangzhou Haiyin Bridge was completed in 1988. In 1995, large-scale corrosion of steel cables occurred, and only cable replacement of the whole bridge could be implemented. The report estimated that the cost of cable replacement was more than ten million yuan [1]. Conventional reinforcement methods such as bonded steel plates and external steel strands have a large self-weight, and their anti-corrosion and anti-fatigue properties are difficult to meet the

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.CH38169

requirements of complex service environments such as salt spray, deicing salt, and severe temperature changes [2]. Carbon fiber reinforced polymers/plastics (CFRP) composites have the characteristics of light weight, high strength, salt erosion resistance, fatigue resistance, and so on. At present, they have been widely used in the treatment of existing bridge diseases and the construction of new bridge main structures.

In 1996, the Storchenbrücke cable-stayed bridge in Switzerland took the lead in using CFRP cables, and the light rail arch bridge in Stuttgart, Germany, used CFRP suspenders to realize the lightweight construction of long-span bridges [3, 4]; the Wuhan Junshan bridge is strengthened with prestressed CFRP plates. The application data introduces the prestressed plate reinforcement technology, showing the practical value of the material in engineering [5].

CFRP reinforcement method has been gradually applied in engineering construction since the 1990s. At the initial stage, the passive reinforcement method of pasting carbon cloth was mainly used. This process has the problem of strain lag, and the high-strength characteristics of the material are not easy to fully display [2]. With in-depth study, the active reinforcement technology of Prestressed CFRP is becoming more and more mature, but the current research still has obvious limitations: Although the single environmental test method of the FRP concrete interface has been summarized, the interface degradation mechanism under the coupling of chloride, fatigue, and temperature lacks systematic compilation [6]. There are differences between the stress calculation assumptions of the current reinforcement code and the stress conditions of the actual bridge in stages with load. The data accumulated from the long-term measurement of the actual bridge durability is not sufficient. There are relatively few studies on the collaborative assessment of the life cycle cost and carbon emissions of CFRP bridges.

According to the existing research results and engineering examples, this paper combs the characteristics of CFRP materials and bridge application technology, analyzes the evolution law of durability damage such as interface debonding and resin aging, summarizes the existing problems of the project, and gives development suggestions from the aspects of material improvement, long-term monitoring, and construction standardization.

2. Basic properties of CFRP composites

2.1. Categories of common CFRP materials for bridges

The CFRP used in bridges uses continuous carbon fiber as the reinforcing phase and epoxy resin as the bonding matrix. It is divided into various categories according to the forming process and form of use to adapt to different reinforcement and bearing requirements. Unidirectional CFRP sheets and prefabricated CFRP sheets are mostly used for external reinforcement. The carbon sheets are flexible and can adapt to the curved surface of special-shaped beams and columns; Prefabricated plates are often used in prestressed active reinforcement systems because of their compact fiber arrangement and greater stiffness. The embedded reinforcement of the surface layer adopts CFRP bars and thin plate strip materials with a regular shape, which is conducive to embedding after the concrete is slotted. In the load-bearing system of long-span bridges, CFRP cables bundled by multiple carbon fiber tendons and provided with protective layers can be used as cables of cable-stayed bridges and suspenders of arch bridges; The carbon fiber horizontal cable of the Changtai Yangtze River Bridge adopts a finished cable composed of 127 carbon fiber tendons with a diameter of 7 mm [7]. CFRP grid is often used to strengthen the thin layer of bridge deck, and its overall application range is relatively narrow.

DOI: 10.54254/2755-2721/2026.CH38169

2.2. CFRP core advantage performance

CFRP has the mechanical properties of light weight and high strength. The use of CFRP for reinforcement or the production of bearing cables will not significantly increase the dead load of the structure, helps to control the long-term downward deflection of the main beam, and meets the construction requirements of long-span lightweight bridges. The fatigue damage mechanism of carbon fiber is different from that of metal, and its fatigue performance is still affected by resin, stress level, and environment. The fatigue test shows that the fatigue performance of the tested CFRP strand is better than that of low relaxation steel strand and stainless steel strand [8]. Using prestressed CFRP to strengthen the beam can delay crack development under fatigue load, and its long-term mechanical performance is good [2]. The results show that carbon fiber has good corrosion resistance and durability, and steel corrosion does not occur, but the performance of the CFRP system is still controlled by the durability of the resin and interface in the dry-wet alternation of chloride and acid-base environment; Using CFRP instead of steel can reduce the failure risk caused by corrosion, reduce the cost of bridge anti-corrosion and operation and maintenance in coastal and deicing salt environment, and is suitable for high corrosion service environment.

2.3. Inherent short plates and typical damage and failure characteristics of CFRP materials

2.3.1. Material defects of CFRP

The tensile properties of CFRP along the longitudinal direction are excellent, but its transverse compressive and shear strength are obviously affected by the properties of the ply and matrix, and its transverse mechanical properties are relatively weak. The heat resistance of the epoxy resin matrix is poor, and its glass transition temperature depends on the formula and curing conditions. The glass transition temperature of the epoxy adhesive used in NSM Research Institute after curing at 23 ℃ for 7 days is 46.2 ℃ [9]. Carbon fiber is conductive. If it is in direct contact with steel, it will cause galvanic corrosion. During construction, it is necessary to set an insulation isolation structure. Long term alkaline solution immersion and water immersion will make the epoxy resin hydrolyze and soften, and reduce the performance of interfacial force transfer; The purchase cost of materials is higher than that of ordinary steel, which limits its application in large-scale projects [2, 6].

2.3.2. Failure mode of CFRP substrate

The failure of a CFRP plate is mainly fiber brittle fracture, without obvious plastic deformation, with sudden failure and poor early warning. It can be inferred that the transverse bearing capacity is weak, which makes the force transfer between layers more dependent on resin and interface; Local stress concentration is easy to promote the propagation of microcracks and induce delamination, weaken the cooperative force between fibers, and finally may cause sudden fracture in the absence of obvious plastic deformation. Environmental aging will produce a large number of microcracks in the resin matrix and fiber-resin interface [6]; In a CFRP plate test, after immersion at 60 ℃ for 224 days, the tensile strength of the non-pre-service specimen decreased by about 33% [10]. Microcrack propagation may further induce delamination damage.

DOI: 10.54254/2755-2721/2026.CH38169

2.3.3. Interface deterioration and failure mode of CFRP concrete reinforcement system

Interface peeling is the main failure mode of CFRP reinforced structures. Under the action of static load at room temperature, the failure mostly occurs in the interior of the concrete substrate; After chlorine salt environmental aging, the adhesive layer may be separated from the concrete surface, and the change in bonding performance depends on the material system and exposure conditions [6]. Under the action of repeated fatigue load, the end of the plate and the anchorage area are prone to local debonding, and the debonding area will continue to expand with the increase of the number of cycles, and eventually lose the ability of collaborative stress [11]. The coupling of high temperature and salt moisture may accelerate resin aging and interface peeling, and increase the failure risk of the reinforcement system. The common failure modes of embedded CFRP reinforcement components are concrete splitting at the slot and the overall pulling out of the reinforcement [9].

3. Evolution law of core application technology and durability of CFRP bridge

3.1. Mainstream engineering application technology and adaptation scenarios

At present, the application of CFRP in bridges is mainly divided into three types: externally bonded reinforcement, embedded reinforcement, and CFRP Cable/reinforcement bearing system. There are obvious differences in the process characteristics, reinforcement effect, and durability performance, which are suitable for different disease conditions and service environments.

Externally bonded CFRP reinforcement mainly includes pasting carbon fiber cloth and prefabricating CFRP plates, which is relatively simple and does not require the use of large equipment. Carbon cloth adapts to special-shaped surfaces; The prefabricated slab has large stiffness, which can cooperate with the prestressed tensioning to form active reinforcement, overcome the strain lag of passive reinforcement, and give full play to the high-strength performance of materials. The application data of the Wuhan Junshan Bridge in Hubei Province introduces the external bonding reinforcement of Prestressed CFRP plate [5]; This kind of active reinforcement can offset the tensile stress caused by partial dead load and restrain the downward deflection of the main beam. However, the external bonding interface is directly exposed to the external environment. Temperature changes and salt corrosion will lead to the aging of the adhesive layer and the reduction of its bonding performance, which requires surface protection measures. The non-anchored externally bonded parts are prone to end spalling. The addition of U-shaped hoops and end-embedded anchorage can delay debonding and strengthen the stability of interface stress [6].

The surface-embedded (NSM) reinforcement technology achieves the reinforcement goal by opening grooves on the concrete surface, embedding CFRP bars or strips, and pouring epoxy adhesive, which can reduce the problem of easy peeling at the end in the external bonding reinforcement, and has achieved good results in bending and shear reinforcement. Its fatigue resistance and aging resistance are affected by the rubber material and groove structure, which can be used for reinforcement research in the presence of salt moisture, freeze-thaw, and other environmental effects. It is often used in bending reinforcement of old beams, repair of cracks in the bottom plate of box girders, and seismic reinforcement of piers. The end anchorage, groove size, and embedded depth will affect the bonding performance of the embedded system, which should be determined in combination with the specific structure. In a 4-year NSM test, the maximum bond degradation after 20 ℃ water immersion is about 12%, indicating that durability still needs to be evaluated according to materials and environmental conditions [9].

DOI: 10.54254/2755-2721/2026.CH38169

As the core lightweight technology of long-span bridges, the CFRP Cable bearing system, with the characteristics of light weight, high strength, corrosion resistance, and fatigue resistance, replaces steel strands and steel cables, and is applied in stay cables, arch bridge suspenders, external prestressed tendons, restraint cables, etc. Storchenbrücke's original report pointed out that under the same breaking load, the weight of CFRP Cable is about one-eighth of that of steel cable [3], which can reduce the additional dead load of the bridge tower and main beam, optimize the internal force, and reduce the whole-cycle anti-corrosion maintenance. CFRP strand tests show good fatigue performance [8], which can adapt to vehicle dynamic load and corrosive environment, and is gradually promoted from the pilot component to the whole bridge; The anchoring system is a technical problem, and the anchoring efficiency and long-term performance of various anchorages need to be determined in combination with the specific structure and test results.

3.2. Deterioration law of interface durability under single environment and load

The bonding interface between carbon fiber reinforced polymer (CFRP) and concrete is the core of the reinforcement system, which directly affects the bearing capacity and durability after reinforcement. Chloride, alkali environment, high temperature, and fatigue load will lead to degradation of interface performance, and the degradation mechanism and damage degree are different under different working conditions.

In the case of chloride erosion, water, chloride, and other media can reach the bonding interface through concrete pores, affecting the adhesive layer and the bonding between the adhesive layer and concrete. After a long period of chlorine salt drying and wetting cycles, the externally bonded parts may change from concrete cohesive failure to interface peeling, and the performance change is related to the rubber material and exposure conditions [6].

In the highly alkaline environment, some resins may undergo hydrolysis or water absorption plasticization, resulting in a large number of microcracks in the matrix, further leading to debonding between fibers and resins [2, 6]. The degree of deterioration depends on the resin formula, solution conditions, and exposure time. When the interface performance is reduced, the end is easily peeled off in advance. The pores and microcracks generated by aging provide a penetration path for the corrosive medium and further accelerate the accumulation of damage.

The root cause of high-temperature degradation is the glass transition of epoxy resin, and its temperature threshold changes with the rubber formula and curing degree. When the glass transition temperature is close to or exceeds the operating temperature, the rubber layer stiffness and force transmission capacity will decrease. Under the condition of cyclic temperature, interface thermal stress will be generated continuously, which will promote the continuous extension of microcracks and affect the interface bonding performance. A 4-year natural exposure and accelerated aging study found that the bond strength degradation was not significant, but the bond stiffness decreased significantly, indicating that different indicators and environments cannot be summarized with a unified annual decay rate [12].

Under the action of simple fatigue load, the damage degree of CFRP reinforcement is low, but it needs to be evaluated according to the specific stress level and material system [8], and the damage is mainly concentrated in the plate end and anchorage area [11]. A CFRP-concrete interface fatigue test found that the bond stiffness evolved in three stages, fatigue failure could occur between the CFRP and adhesive layer, and the shear damage continued to accumulate, eventually leading to the loss of the system's collaborative stress capacity [11].

DOI: 10.54254/2755-2721/2026.CH38169

3.3. Evolution characteristics of durability under multi-field coupling conditions

The actual bridge is subject to the coupling effect of many factors during service. Chloride, temperature change, fatigue, and freeze-thaw may affect each other and accelerate interface degradation. The degree depends on the material system and environmental history, which is the key and difficult point of durability research.

Under the coupling effect of salt, moisture, and temperature change, the temperature gradient may accelerate the migration of water and chloride ions to the interface and affect resin aging and interface force transfer. The long-term exposure study further showed that the material combination had a significant impact on the results: in a 110-month study, the ultimate bond strength of CFRP plate/sika30, CFRP cloth/sw3c, and CFRP plate/araldite106 systems decreased by about 3%, 9%, and 36%, respectively, after wet-dry cycles, and the loss rate of a certain system could not be extended to all reinforcement systems [13].

The coupling between load and corrosion forms a vicious cycle: the fatigue alternating shear stress makes the interface microcracks open, which is convenient for the invasion of corrosive media; Corrosion will reduce the interface stiffness and further aggravate the stress concentration. The Related Durability review points out that environmental aging will reduce the fatigue life and bonding performance; These research conclusions cannot be directly equivalent to the ten-year performance of the real bridge [6].

The coupling effect of freeze-thaw and chloride salt is common in bridges using deicing salt in the north. Freezing and thawing alternately cause the water in the concrete pores to freeze and expand, and cause damage. The surface layer is loose and falls off, accelerating the invasion of chloride ions; Salt crystal expansion continues to open cracks, while damaging the substrate and bonding surface. In a coupling test using 3.5% NaCl solution, after 300 freeze-thaw cycles, the shear bearing capacity of CFRP concrete joints decreased by about 12%, and the failure position shifted from the inside of the concrete to the interface between the adhesive layer and the concrete [14].

3.4. Key technologies for durability improvement and protection

In view of the shortage of CFRP materials, interface debonding, and aging, the existing protection methods mainly include material improvement, structural reinforcement, surface protection, and standardized construction, which can delay the deterioration of the system and further improve the stability of long-term service.

In terms of material modification, silane coupling agents, nano fillers, and surface treatment are research directions to improve interface durability. The research on silane treatment and nano modification to improve the interface performance of epoxy concrete has been summarized, but the effect is affected by the material formula and exposure conditions, and can not be expressed by a unified strength improvement ratio [6]. Plasma and other surface modification methods can be used as further research directions, and their long-term effect in an alkaline environment still needs to be verified by specific experiments.

Structural improvement: the embedded reinforcement adds mechanical anchorage at the end, and the external reinforcement is equipped with U-shaped hoops to improve the ultimate bearing capacity of the interface and slow down the growth rate of debonding in the coupling environment [6, 9]. UHPC thin-layer coating can be used as the research scheme for barrier protection in the reinforced area, and its impermeability effect and compatibility with the CFRP interface and construction joint need to be specially verified. Multi-point anchoring can disperse the interface shear stress of the prestressed system and reduce the risk of local peeling.

DOI: 10.54254/2755-2721/2026.CH38169

Surface protection: apply weather-resistant anti-corrosion paint and polyurethane topcoat, which can be used to reduce the direct effect of UV and external media; When the anti-crack protective layer is used in the northern freeze-thaw area, it is also necessary to check the compatibility and long-term effect, and the protection ability of a specific coating cannot be regarded as a fixed improvement ratio.

Construction and Monitoring Optimization: carry out grinding, dust removal, and activation operations on the concrete base to improve bonding conditions and reduce congenital defects. Optical fiber sensing can be used to monitor the strain and other responses of reinforced components. Nonlinear ultrasonic methods have been used to identify the debonding of the FRP-concrete interface [15]. The specific detection accuracy depends on the sensor layout, components, and algorithms. The combination of the above monitoring methods and normalized preventive maintenance can help to identify the stripping risk in advance and improve the durability of the bridge throughout its life cycle.

4. Limitations and prospects

4.1. Industry bottlenecks

Based on the research results of material properties, engineering applications, and durability, there are still many limitations in the promotion of CFRP in bridge engineering.

In terms of materials, the transverse compressive and shear capacity of CFRP is weak; Epoxy resin is prone to deterioration in high-temperature environments; Carbon fiber is conductive, and galvanic corrosion will occur when it contacts steel; The relatively high price of materials restricts its large-scale application. Alkali, chloride, and temperature cycling may cause degradation of resin and interface properties, promote the extension of interface microcracks, and further induce interface peeling failure.

In terms of engineering application, the research on the three technologies of external sticking, embedded, and prestressed cable is relatively independent, lacking a unified design and analysis scheme; The calculation assumptions of the current code are inconsistent with the actual stress conditions of the bridge in stages with load, and the durability design items of multi-field coupling are not perfect.

In terms of durability research, most of the current tests use single environment accelerated aging method, which is significantly different from the service status of the real bridge with multi factor coupling; Lack of long-term monitoring data on field bridges; The constitutive relation and life prediction theory of interface degradation are not mature enough; There are few studies on collaborative assessment of CFRP bridge life cycle cost and carbon emissions, which is difficult to support low-carbon transportation decisions.

4.2. Development prospect

4.2.1. Modification and optimization of composite matrix

In view of the softening of resin and the decline of interface performance in hot and humid environments, the research and development of temperature-resistant and corrosion-resistant epoxy resin should be strengthened, and its hydrolysis resistance and long-term bonding stability should be taken into account while improving the glass transition temperature. The interface bonding is improved by silane treatment and nano filler modification, and the modification effect is evaluated

DOI: 10.54254/2755-2721/2026.CH38169

in combination with the change of strength and stiffness after aging, so as to gradually form a material system with appropriate cost and convenient construction.

4.2.2. Improve the specification system and standardized construction technology

Under the action of long-term environment, the bonding strength, stiffness, and failure location of the interface may change to varying degrees. These effects should be gradually considered in the design and calculation, and the simplified assumptions based on the initial material properties should be improved. The interface stiffness, peak bond stress, and other parameters in the bond slip relationship can be modified by combining the freeze-thaw times and exposure time, and the stress differences in different construction stages in prestressed reinforcement can be considered. At the same time, the quality requirements for base treatment, adhesive curing, end anchoring, and surface protection are clarified to reduce the impact of construction defects on long-term performance.

4.2.3. Development of durable protection system and long-term monitoring technology

Different material combinations show significant differences in durability under long-term exposure. Protective measures should be selected in combination with the characteristics of rubber materials and the environment where the bridge is located, and the synergistic effect of surface coating, UHPC coating, and mechanical anchorage should be further studied. Long term monitoring should focus on the plate end and anchorage area, combine optical fiber strain monitoring with ultrasonic debonding detection, timely identify local force transmission abnormalities, and gradually improve the damage early warning and maintenance judgment basis through real bridge observation.

4.2.4. Broaden engineering application and collaborative research in the whole life cycle

While expanding the application of CFRP bridges, the long-term performance changes should be included in the economic and carbon emission evaluation, and the links of material production, construction, inspection, maintenance and replacement should be comprehensively considered. Combined with the durability differences of different rubber materials and protection schemes, the relationship between initial investment and later maintenance needs is analyzed to avoid judging the advantages and disadvantages of schemes only by material consumption or short-term reinforcement effect, so as to provide a basis for the rational application of CFRP in bridge engineering.

5. Conclusion

In this paper, the application and durability of CFRP composites in bridge structures are compared and analyzed. The performance characteristics of CFRP materials commonly used in bridges are sorted out, and the process characteristics and application status of three mainstream technologies, namely external reinforcement, embedded reinforcement, and CFRP cable reinforcement bearing system, are compared. The Degradation Laws of the CFRP-concrete interface under single-environment and multi-field coupling are summarized, and the durability improvement technologies are summarized. The existing bottlenecks in the industry are analyzed. The main conclusions are as follows:

CFRP has the advantages of light weight, high strength, good corrosion resistance, and excellent fatigue resistance, which is suitable for bridge reinforcement in corrosive environments and lightweight construction of long-span bridges. However, the transverse shear and compression resistance of the material is not good; the high-temperature resistance of the epoxy resin matrix is

DOI: 10.54254/2755-2721/2026.CH38169

not enough; carbon fiber is prone to galvanic corrosion with steel; and the cost is relatively high, which limits its large-scale application. The failure is mainly brittle fracture, and resin hydrolysis and interface microcrack propagation are the main causes of aging damage.

Each of the three engineering technologies has its own advantages and disadvantages: external bonding reinforcement is easy to operate, but the interface is prone to end debonding, which needs to be combined with anchoring and protection means; Embedded reinforcement can effectively reduce the peeling problem, and its environmental durability still depends on the rubber material and structure; CFRP cable reinforcement system can significantly reduce the additional dead load of long-span bridges, and the anchoring system is the main control point of its reliability.

Chloride, high temperature, alkali, and fatigue load will lead to degradation of interface performance. Multifield coupling may increase the damage effect and accelerate the failure processes such as interface debonding, concrete splitting, and reinforcement pulling out. Through matrix and fiber modification, adding anchorage structure, using UHPC coating, implementing surface protection, and carrying out standardized construction, it is expected to delay the deterioration of the interface, but the specific protection combination needs to be verified. The use of optical fiber and ultrasonic detection can realize the early identification of damage and provide support for preventive maintenance work.

At this stage, the design system of CFRP bridges is not unified, the relevant specifications for multi-field coupling durability are lacking, and the long-term monitoring data of actual bridges are not enough. Subsequently, it is necessary to reduce the cost of matrix modification, improve standards and specifications, establish a long-term monitoring mechanism, and implement a comprehensive life cycle assessment to promote the standardized and large-scale application of CFRP in bridge engineering.

References

[1] Hou, B. (2018, June 7). Analysis of typical corrosion failure cases of highway bridges. *China Corrosion and Protection Network*. (in Chinese). https://www.corrdata.org.cn/secondPath/bridge/2018-06-07/169026.html

[2] Ortiz, J. D., Khedmatgozar Dolati, S. S., Malla, P., et al. (2023). FRP-reinforced/strengthened concrete: State-of-the-art review on durability and mechanical effects. *Materials, 16*(5), Article 1990. https://doi.org/10.3390/ma16051990

[3] Meier, H., Meier, U., & Brönnimann, R. (1996). Zwei CFK-Kabel für die Storchenbrücke [Two CFRP cables for the Storchenbrücke]. *Schweizer Ingenieur und Architekt, 114*(44), 980–985. (in German). https://doi.org/10.5169/seals-79069

[4] Raabe, N., & Hagmann, M. (2022, August 3). Civil engineering award for construction art with Swiss contribution. *Sciena*. https://www.sciena.ch/tech-transfer/civil-engineering-award-for-construction-art-with-swiss-contribution.html

[5] Shanghai Horse Construction Technology Co., Ltd. (2022, June 10). What strengthening problems can the prestressed carbon fiber plate strengthening system solve? (in Chinese). https://m.shhorse.com/Article/yyltssxwbjgx_1.html

[6] Tatar, J., & Milev, S. (2021). Durability of externally bonded fiber-reinforced polymer composites in concrete structures: A critical review. *Polymers, 13*(5), Article 765. https://doi.org/10.3390/polym13050765

[7] Bai, L. (2024, August 16). A river of clear water and a myriad of mountains | Changtai Yangtze River Bridge welcomes another world-class breakthrough! Erection of carbon fiber horizontal stay cables for the main channel bridge completed. *China Jiangsu Network*. (in Chinese). https://jsnews.jschina.com.cn/zt2024/yjqswcs/202408/t20240816_3447482.shtml

[8] Grace, N. F., Mohamed, M. E., & Bebawy, M. R. (2023). Evaluating fatigue, relaxation, and creep rupture of carbon-fiber-reinforced polymer strands for highway bridge construction. *PCI Journal, 68*(3), 36–61. https://doi.org/10.15554/pcij68.3-01

[9] Dushimimana, A., Sena-Cruz, J., Correia, L., et al. (2024). Effects of long-term exposure of NSM CFRP-to-concrete bond to natural and accelerated aging environments. *Composite Structures, 340*, Article 118174.

DOI: 10.54254/2755-2721/2026.CH38169

https://doi.org/10.1016/j.compstruct.2024.118174
[10] Alsuhaibani, E., Yazdani, N., & Beneberu, E. (2022). Durability and long-term performance prediction of carbon fiber reinforced polymer laminates. *Polymers, 14*(15), Article 3207. https://doi.org/10.3390/polym14153207
[11] Kallel, A., Masmoudi, R., Bissonnette, B., & Joanis, M. (2024). Bond behavior of CFRP reinforcement systems with concrete under static and fatigue loading. *Construction and Building Materials, 426*, Article 136000. https://doi.org/10.1016/j.conbuildmat.2024.136000
[12] Dushimimana, A., Sena-Cruz, J., Correia, L., et al. (2024). Durability of bond between EBR-CFRP laminate and concrete after four years of natural outdoor and accelerated ageing exposures. *Construction and Building Materials, 427*, Article 136213. https://doi.org/10.1016/j.conbuildmat.2024.136213
[13] Hao, Z. H., Zeng, J. J., Chen, G. M., et al. (2024). Durability of FRP-to-concrete bonded joints subjected to 110 months accelerated laboratory and field exposure. *Engineering Structures, 305*, Article 117681. https://doi.org/10.1016/j.engstruct.2024.117681
[14] Kallel, A., Ahmed, M., Metiche, S., & Masmoudi, R. (2026). Durability investigation of the bond behavior of CFRP-concrete interface and the tensile properties of CFRP and adhesive layer, under combined effect of salt and freeze-thaw cycles. *Construction and Building Materials, 532*, Article 146729. https://doi.org/10.1016/j.conbuildmat.2026.146729
[15] Cao, Y., Ng, C. T., & Smith, S. T. (2023). Debonding detection in FRP-strengthened concrete structures utilising nonlinear Rayleigh wave mixing. *Measurement, 214*, Article 112736. https://doi.org/10.1016/j.measurement.2023.112736