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Research Status of BFRP Strengthening Concrete Structures with Different Damage Types

Junli Liu, Longjiu Jian, Sisi Zhang

School of Urban Construction, Yangtze University, Jingzhou, China

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Abstract: Concrete structures are prone to various types of damage over time, including compressive damage, high-temperature fire damage, freeze-thaw damage, and seismic damage. These damages directly affect the safety and durability of concrete structures and may even lead to structural failure. Traditional strengthening methods, such as steel reinforcement or steel plate bonding, increase the structural weight and introduce construction challenges. Additionally, materials used in these methods are prone to corrosion, which is difficult to control. In contrast, the recently developed Basalt Fiber Reinforced Polymer (BFRP) strengthening method offers high strength, excellent corrosion resistance, and lightweight properties, making it an ideal solution for repairing and strengthening concrete structures. This paper summarizes the strengthening mechanisms and effects of BFRP on concrete structures subjected to compressive damage, high-temperature fire damage, freeze-thaw damage, and seismic damage. It also briefly discusses current research limitations and future directions.

1. Introduction

During their service life, concrete structures experience various types and degrees of damage due to environmental factors, self-weight, external forces, or material degradation. For lightly damaged components, technical interventions can restore functionality and minimize losses. As global infrastructure ages, the repair and strengthening of concrete structures will become a key focus in civil engineering. Traditional strengthening methods, such as steel reinforcement or external steel plate bonding, are heavy, labor-intensive, and susceptible to corrosion. In contrast, BFRP exhibits excellent mechanical properties and corrosion resistance, making it an ideal strengthening material. Common BFRP strengthening techniques include BFRP wrapping, BFRP grid reinforcement, and BFRP bar composite reinforcement, as shown in Figures 1–3. Due to its lightweight, corrosion resistance, and high tensile strength, BFRP shows great promise for repairing various types of damaged concrete structures[1,3].

This paper discusses the strengthening mechanisms and effects of BFRP on concrete structures with four common damage types: compressive damage, high-temperature fire damage, freeze-thaw damage, and seismic damage.

Figure 1: BFRP fabric

Figure 2: BFRP grid

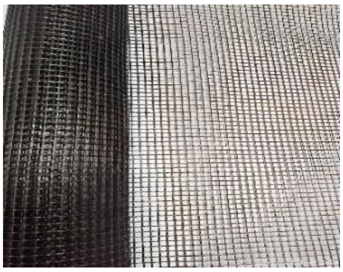

Figure 3: BFRP bar

2. Basic Properties of BFRP

Basalt Fiber Reinforced Polymer (BFRP) is a composite material composed of basalt fibers and a polymer resin matrix. Its applications in civil engineering are increasing, and this section summarizes its key properties:

a) High tensile strength and elastic modulus: BFRP has a tensile strength of 2800–3100 MPa, an elastic modulus of 80–90 GPa, and an elongation rate of approximately 3.1%. Compared to Glass Fiber Reinforced Polymer (GFRP), BFRP exhibits higher strength and modulus. Although its strength is slightly lower than Carbon Fiber Reinforced Polymer (CFRP), BFRP offers cost advantages [2].

b) Excellent corrosion resistance: BFRP performs well in acidic, alkaline, and saline environments, with less degradation than GFRP under the same conditions. It also maintains high mechanical properties at elevated temperatures, making it suitable for bridges and marine structures [3].

c) High-temperature resistance: BFRP can operate within -200 ℃ to 800 ℃ and withstand short-term exposure to 750 ℃. Its glass transition temperature ranges from 125 ℃ to 135 ℃, making it suitable for high-temperature applications, such as post-fire structural strengthening [4,5].

d) Eco-friendliness and abundant resources: BFRP is made from basalt fibers, which are widely available. Its production is energy-efficient and environmentally friendly, and it can be recycled after use, aligning with green building trends [6,7]. BFRP is also cost-effective, with production costs lower than CFRP but slightly higher than GFRP.

3. Research on BFRP Strengthening of Concrete Structures with Different Damage Types

Compressive damage typically occurs at support points or areas under sustained pressure in concrete structures. Long-term compression reduces the compressive strength of concrete, leading to crushing or cracking. BFRP wrapping can restrain the axial and radial tensile stresses generated during compression, inhibit concrete expansion, and significantly improve axial compressive capacity and ductility. Compared to unstrengthened concrete, BFRP-confined concrete effectively suppresses crack propagation, with ultimate strain capacity increasing by 5.9–10.5 times [8,9].

Ma et al. [8,10] conducted axial compression tests on pre-damaged concrete cylinders and prisms with varying BFRP layers. The results showed that BFRP provides triaxial confinement, enhancing the ultimate strength and strain of damaged columns. However, the initial stiffness reduced by damage cannot be restored. Huang Jingting [11] compared unidirectional and bidirectional BFRP wraps, finding that unidirectional wraps offer better mechanical performance, while bidirectional wraps exhibit 75% of the strength and 15% lower elongation. Factors such as grid size, surface treatment, and protective layer thickness also influence the strengthening effect. Zhang Xiaofei et al. [12] noted that larger grid sizes inhibit spalling but may hinder multi-cracking development, reducing flexural performance. Sand-coated surface treatments enhance interfacial bonding and improve bending resistance.

In summary, the application of BFRP confinement for strengthening concrete structures can effectively restrain concrete cracking and retard crack propagation, thereby enhancing structural load-bearing capacity. The damage level, number of package layers, grid size and surface treatment method all affect the ultimate strength and strain after reinforcement. However, current research on damaged concrete reinforcement predominantly employs macroscopic preloading simulations to replicate damage states, while the multi-scale damage evolution mechanisms remain an area requiring further investigation.

3.1. High-Temperature Fire Damage

High-temperature fire exposure causes significant deterioration in the physical, chemical, and mechanical properties of concrete. At temperatures above 200 ℃, hydration products (e.g., C-S-H, $Ca(OH)_2$) decompose, increasing porosity and internal cracking. At 600–800 ℃, concrete loses 40–80% of its compressive strength, irreversibly [13]. High-strength concrete is more prone to spalling due to its dense structure and high water content. Additionally, heated steel rebars experience reduced yield strength and degraded interfacial bonding [14].

BFRP demonstrates superior cost-effectiveness and environmental adaptability compared to CFRP, rendering it particularly advantageous for post-fire structural rehabilitation. The BFRP wrapping technique involves the application of BFRP sheets in specified configurations and quantities to form a reinforced BFRP mesh system. This confinement mechanism effectively controls externally applied constraint stresses, mitigates concrete expansion-induced cracking, and consequently enhances the ultimate bearing capacity, ductility, and deformation capability of structural members [15].Extensive experimental investigations conducted by domestic and international researchers on BFRP-strengthened post-high-temperature concrete structures have consistently demonstrated that BFRP reinforcement can increase the ultimate load-bearing capacity of fire-damaged concrete components by approximately 20%-100%, with particularly pronounced effectiveness for structures subjected to mild-to-moderate fire damage [15,19]. Zhang Xin [16]employed the ISO834 standard heating curve to thermally treat reinforced concrete cylindrical specimens, subsequently strengthening them with 1-4 layers of BFRP wraps in varying configurations. The experimental results revealed that the three-layer full-wrap configuration yielded maximum strength enhancement (20%-60% increase), while excessive wrapping layers exhibited diminishing returns due to saturation effects.

Ouyang Lijun et al. [17,18] conducted experimental studies on BFRP-confined post-fire concrete cylinders and square columns, introducing the concept of "effective ultimate tensile strain" to quantitatively characterize temperature effects on BFRP confinement efficiency. Their findings indicated an inverse relationship between temperature exposure and actual stress levels in BFRP, though ductility improvements remained significant. The developed temperature-dependent strength and strain prediction model incorporated critical parameters including lateral confinement stress, temperature degradation coefficients, and wrapping layer numbers, demonstrating satisfactory predictive accuracy. Internationally, Bisby et al. [19]performed rehabilitation experiments on actual fire-damaged concrete columns, confirming that BFRP strengthening could effectively restore post-fire ultimate capacity and modify failure modes from brittle crushing to ductile bulging. Additional research highlights that although BFRP exhibits superior high-temperature performance relative to CFRP, its interfacial bond performance with concrete undergoes significant degradation after thermal exposure, potentially compromising the overall strengthening efficacy.

Although current research on BFRP-strengthened high-temperature concrete structures has established a preliminary foundation, the existing models exhibit notable limitations. Most predictive models are extended from ambient-temperature formulations and fail to systematically account for interfacial bond degradation. Furthermore, the simulated fire scenarios typically assume uniform heating conditions and neglect multiaxial stress states. Moreover, there is currently no specialized design code for post-fire BFRP strengthening applications, with current practice predominantly relying on experimental data and empirical judgment.

3.2. Freeze-Thaw Damage

Freeze-thaw cycling induces microstructural damage in concrete and leads to degradation of its macroscopic mechanical properties. It is generally recognized that increasing freeze-thaw cycles progressively reduce the dynamic elastic modulus, mass retention ratio, and compressive strength of concrete, with structural performance deteriorating rapidly after exceeding 100 cycles [20]. Additionally, Chang Hong et al. experimentally demonstrated a positive correlation between the number of freeze-thaw cycles and strength reduction, accompanied by a transition in failure mode from ductile to brittle fracture [20].BFRP exhibits excellent freeze-thaw resistance, demonstrating significant potential for structural reinforcement in cold regions. Its primary strengthening mechanism involves providing lateral confinement through external wrapping, thereby enhancing the triaxial compressive state of concrete, inhibiting crack propagation, and improving ductility. Research confirms that BFRP strengthening can substantially improve both axial compressive capacity and deformation capability of freeze-thaw damaged concrete members. Zhang Hongjia's experimental study on strengthening freeze-thaw damaged short columns concluded that triple-layer BFRP wrapping increased ultimate bearing capacity by approximately 37% while enhancing ultimate deformation capacity by 51.2% [21]. Li Zhiqiang employed ABAQUS simulations to verify that post-strengthening structural damage parameters correlate closely with wrapping layers, subsequently developing a predictive model for mechanical performance enhancement [22].

The interfacial bonding performance between BFRP and concrete constitutes a critical factor determining reinforcement effectiveness. However, BFRP's inherent material brittleness tends to generate numerous interfacial cracks under freeze-thaw cycling, adversely affecting stress transfer. Li Bangbang investigated BFRP-concrete interfacial bond degradation under coupled freeze-thaw-fatigue conditions using three-dimensional finite element analysis, identifying interfacial softening zone expansion and effective bond length reduction as primary influencing mechanisms [23]. Du Wenjie established a bond-slip relationship model through numerical computation, demonstrating progressive deterioration of interfacial shear performance with increasing cycle numbers [24].Freeze-thaw damage not only reduces structural load-bearing capacity but also compromises seismic performance. Gong Yanan developed finite element models of freeze-thaw damaged RC columns with varying BFRP reinforcement layers, subjecting them to low-cycle reversed loading. The experimental results demonstrated significant improvements in both ductility and energy dissipation indicators after reinforcement [25].

While current research has achieved notable progress, several limitations remain: (1) the absence of unified quantitative evaluation criteria for freeze-thaw damage; (2) insufficient elucidation of microscopic evolution mechanisms governing interfacial bond performance; and (3) incomplete understanding of strengthening performance evolution under multi-factor coupling conditions, warranting further investigation.

3.3. Seismic Damage

Seismic damage typically occurs in concrete structures subjected to earthquake or vibrational loading, manifesting as yielding, cracking, and shear failure, which compromise both load-bearing capacity and ductility, potentially leading to structural collapse in severe cases [26]. The seismic strengthening mechanism of BFRP primarily involves: (1) providing lateral confinement to restrain concrete expansion cracks; (2) preventing steel reinforcement buckling to enhance column hysteretic performance; and (3) transforming failure modes from brittle shear to ductile flexural behavior [27].

Regarding strengthening methodologies, Liu Chen [27] conducted a comparative analysis of various BFRP techniques including filament winding, fabric wrapping, bar/fabric hybrid systems, and grid reinforcement. The study revealed that filament winding provides optimal ductility enhancement despite complex installation, while fabric wrapping offers construction convenience with limited capacity improvement. The bar/fabric hybrid demonstrates balanced performance in both capacity and ductility enhancement, with grid systems being particularly suitable for specialized applications like bridge pile foundations. For different column sections, Huang Jingting et al. [28] performed low-cycle reversed loading tests on BFRP-wrapped RC circular and square columns. Results indicated 24.2%-34.9% increases in load capacity, 114.7%-131.4% improvements in ductility coefficients, and 5%-9.4% enhancements in equivalent viscous damping coefficients. Square columns exhibited more brittle failures due to corner stress concentrations, whereas circular columns showed superior ductility improvements owing to more uniform confinement. Yang Dejian [29] employed ANSYS finite element simulations to quantitatively evaluate three BFRP configurations (end-wrapping, uniform-wrapping, and mid-span wrapping) for rectangular RC columns. The analysis demonstrated that end-wrapping increased ultimate load by 18% and ductility by 396%, while mid-span wrapping produced slender hysteresis loops with poor energy dissipation capacity. Ma Cuiling et al. [30] compared strengthening effects on circular RC columns with varying concrete strengths, establishing that BFRP outperforms CFRP in enhancing ductility and energy dissipation for low-to-medium strength columns, and proposed corresponding capacity and ductility calculation formulas for FRP-confined circular columns. Zhou Yunyu et al. [31]investigated BFRP-strengthened RC frame joints, reporting 15% shear strength improvement, significantly enhanced ductility, and more robust hysteresis loops post-strengthening.

In summary, sustained scholarly efforts have advanced research on BFRP for post-earthquake structural rehabilitation, with progressive refinements in: (1) strengthening methods for diverse column sections; (2) multi-hazard coupling environments; and (3) numerical simulation and constitutive modeling. These developments demonstrate promising applications for BFRP in seismic-damaged structures. However, critical knowledge gaps remain regarding: (1) unified micromechanical models for interfacial slip and debonding mechanisms under dynamic loading; (2) accurate prediction of hysteretic behavior; and (3) precise simulation of damage accumulation and performance degradation under low-cycle fatigue loading - all requiring further research refinement.

4. Conclusions and Prospects

In recent years, Basalt Fiber Reinforced Polymer (BFRP) has emerged as a novel high-performance fiber composite material demonstrating excellent applicability in addressing the degradation of concrete structures subjected to various deteriorating environments, including fire, high temperatures, freeze-thaw cycles, and seismic actions. BFRP strengthening exhibits remarkable adaptability and effectiveness for diverse types of damaged concrete structures. Research findings confirm that BFRP reinforcement significantly enhances structural compressive capacity, ductility, and energy dissipation capability, while effectively controlling crack propagation and interfacial debonding, thereby improving structural durability and operational safety. Specifically, for seismic-damaged components, BFRP confinement improves hysteretic behavior and ductility; in freeze-thaw environments, BFRP demonstrates superior water resistance and interfacial stability compared to CFRP and GFRP; and for post-fire rehabilitation, modified epoxy adhesives or layered wrapping techniques can effectively restore mechanical performance.

Although extensive experimental and numerical studies have validated BFRP's applicability to various damaged concrete structures, several critical challenges remain: (1) systematic comparisons of BFRP strengthening mechanisms and effectiveness across different damage modes are still lacking; (2) the influence of complex environmental conditions (e.g., coupled high-temperature-freeze-thaw-fatigue effects) on the durability of BFRP-strengthened structures requires further investigation; (3) interfacial bond degradation, constitutive model accuracy, and standardized strengthening procedures need refinement; and (4) current BFRP constitutive models exhibit insufficient precision. Future research should focus on lifecycle design strategies for post-disaster structural performance recovery, enhance service behavior monitoring and theoretical modeling under multi-physics coupled environments, and promote the standardization, intellectualization, and industrialization of BFRP strengthening technologies. These advancements will fully unlock BFRP's engineering potential in infrastructure maintenance and post-disaster reconstruction.

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