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Study on the Fire Resistance of Reinforced Concrete Structures Strengthened with Carbon Fiber Fabric

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Abstract

High temperatures during fires pose a serious threat to the safety of building structures, significantly degrading the mechanical properties of construction materials and potentially triggering major accidents. Elevated thermal exposure reduces the mechanical performance of reinforced concrete (RC) elements, substantially undermining their overall behavior. Moreover, under high-temperature conditions, the epoxy-based bond between carbon fiber fabric and the concrete substrate undergoes pronounced thermal degradation, placing unprotected, strengthened structures at significant risk of compromised structural integrity. This study systematically reviews the existing literature, focusing on RC members strengthened with carbon fiber fabric to investigate their fire resistance limits and failure mechanisms under fire-induced high temperatures. Several insights and recommendations are proposed based on this review.

Keywords

Carbon fiber fabric; Reinforced concrete structures; Fire resistance.

1. Introduction

With the ongoing development of high-rise and long-span structures, reinforced concrete (RC) has become widely used due to its excellent load-bearing capacity and durability. However, RC members subjected to fire are prone to concrete spalling, steel reinforcement buckling, and bond deterioration, all of which critically endanger structural safety. As a lightweight, high-strength, and corrosion-resistant external reinforcement material, carbon fiber fabric (CFRP) can be bonded to the surface of RC components to significantly enhance their strength and stiffness. This review focuses on the research progress of fire resistance of RC structures strengthened with carbon fiber sheets, systematically analyzes the existing research results, and provides reference for further research in this field.

2. Research Content

2.1. Concrete Beams

Wu et al. [1] developed a computational program to analyze the temperature field and fire resistance limit of reinforced concrete beams strengthened in flexure with carbon fiber fabric. Their results indicate that increasing the thickness of the fire-protective coating, the concrete cover depth, and the tensile-reinforcement ratio all extend the fire resistance limit of the strengthened beam. Conversely, the fire resistance limit decreases with higher load ratios, larger amounts of carbon fiber fabric, and greater span-to-depth ratios—among which the load ratio has the most pronounced effect. Li et al. [2] conducted experimental studies on simply supported reinforced concrete beams strengthened with carbon fiber fabric bonded using alkali–slag cementitious material, examining their behavior during and after fire exposure. The results showed varying degrees of reduction in the post-fire flexural capacity of the specimens, likely due to the significant shrinkage deformation of the alkali–slag binder under elevated temperatures. Wu et al. [3] compared unstrengthened reinforced concrete beams with beams

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flexurally strengthened using carbon fiber fabric under three-sided fire exposure to investigate the effects of thick fire-protective coating thickness, load ratio, and carbon fiber fabric amount on fire performance. The results indicated that, under high temperatures, the failure modes of such members could be categorized as either flexural failure or flexural-shear failure. Although the strengthened beams carried substantially higher loads than the unstrengthened beams, their fire resistance limit was still superior due to the protection provided by the fire coating. Increasing the amount of carbon fiber fabric not only tended to extend the fire resistance limit of the strengthened members but could also lead to a shift in the failure mode. Li et al. [4] compared the fire performance of end-restrained concrete beams strengthened with carbon fiber fabric to that of unstrengthened beams, examining the effects of axial and rotational end restraints, fire-protective coating thickness, and load ratio on deformation and internal forces at elevated temperatures. Test results showed that the maximum axial deformation of restrained beams decreased with increasing axial restraint stiffness ratio and coating thickness; the maximum additional axial force increased with higher axial restraint stiffness ratio or thinner coating; and the maximum additional end moment increased as the coating thickness decreased, though the variation was relatively small when the thickness ranged between 10 and 20 mm. Upon cooling, the additional axial force of the restrained beams recovered only slightly, while the additional end moment dropped significantly. Compared with unstrengthened beams, the strengthened beams exhibited not only smaller peak additional end moments but also a substantial delay in their occurrence. Liu et al. [5] conducted high-temperature tests comparing the fire resistance of beams flexurally strengthened with carbon fiber fabric to unstrengthened control beams, applying a non-intumescent fire-protective coating to the CFRP surface of the strengthened specimens. The results indicated that spalling of the bottom concrete significantly altered the high-temperature failure location of the strengthened beams. Under load ratios not exceeding 0.5, the strengthened specimens still met the 2-hour fire resistance requirement for Class I rating.

Wei [6] compared strengthened and unstrengthened concrete beam specimens to investigate the evolution of load-bearing performance degradation in strengthened beams under different load levels during fire exposure. The findings revealed that appropriately designed fire protection measures effectively reduced internal temperatures and improved the fire resistance of strengthened beams, whereas increasing the load level led to a reduction in fire resistance limits.

2.2. Concrete Columns

Xiao et al. [7] conducted fire tests to compare the failure modes, cross-sectional temperature fields, axial deformation, and fire resistance ratings of two CFRP-strengthened reinforced concrete (RC) columns—each using a different adhesive—with an unstrengthened RC column. The results showed that the confinement provided by CFRP sheets bonded with organic adhesive failed within minutes of fire exposure, whereas CFRP sheets bonded with inorganic adhesive continued to provide effective lateral pressure to the core concrete even after several tens of minutes under fire conditions. For the same fire exposure duration, the temperature field across the section of CFRP-strengthened concrete columns was lower than that of the unstrengthened column. However, there was no significant difference in temperature distribution between columns reinforced with inorganic and organic adhesive-bonded CFRP sheets. Overall, columns reinforced with inorganic adhesive-bonded CFRP exhibited superior fire resistance and achieved a fire resistance rating comparable to unstrengthened columns subjected to the same load ratio. Qi [8] investigated the mechanical properties of conventional RC columns and CFRP composite-strengthened RC columns. The findings indicated that the dual protection provided by the steel tube and the annular concrete layer effectively insulated against heat transfer, thereby reducing the temperature within the composite-strengthened RC

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columns. For RC columns, both fire exposure duration and the thickness of the protective layer significantly affected the temperature distribution, while changes in stirrup spacing had a minimal effect. In the case of composite-strengthened RC columns, the thickness of the annular concrete, the steel tube, and the duration of fire exposure all influenced the temperature field, with annular concrete thickness and fire duration being the most significant factors. The effect of steel tube thickness was relatively minor. As both fire exposure time and eccentricity increased, the load-bearing capacity of the composite-strengthened columns gradually decreased. However, for a given fire exposure duration, increasing the thicknesses of the steel tube and the annular concrete layer improved the load-bearing capacity. Wang [9] performed a comparative analysis of the high-temperature performance between composite-strengthened structures and conventional RC members. The results showed that the composite-strengthening approach significantly improved the fire resistance of FRP materials. Furthermore, the synergistic interaction among the steel tube, concrete, and CFRP enhanced the ultimate load-bearing capacity of structural columns. Liu [10] conducted finite element simulations to study the temperature field of CFRP-strengthened RC column sections under fire conditions. The analysis considered scenarios both with and without fire protection layers. By comparing the effects of different fire protection layer thicknesses on the temperature field, the study determined the optimal protection thickness required to ensure the safe performance of the CFRP material.

2.3. Concrete Slabs

Wu et al. [11] conducted comparative fire resistance tests on three CFRP-strengthened reinforced concrete slabs—each using different fire protection materials—and one unstrengthened slab under ISO 834 standard fire conditions. The results showed that, with appropriate fire protection measures, CFRP-strengthened slabs can maintain fire resistance limits comparable to or even exceeding those of unstrengthened slabs, even under significantly increased service loads. Wu et al. [12] further analyzed the high-temperature behavior of CFRP-strengthened concrete slabs under varying conditions, including different slab sizes, fireproof coating thicknesses, tensile reinforcement ratios, amounts of CFRP reinforcement, concrete cover thicknesses, and load ratios. The results indicated that under high temperatures, the fire resistance of CFRP-strengthened slabs increased with greater slab thickness, thicker fireproof coatings, and thicker concrete cover layers, but decreased with higher amounts of CFRP reinforcement and increased load ratios. Among these factors, the load ratio had the most significant impact, while the tensile reinforcement ratio had a relatively minor effect on the fire resistance of such strengthened components. Zhang [13] explored the use of inorganic adhesive MOC (magnesium oxychloride cement) as a substitute for epoxy resin-based adhesives in bonding CFRP sheets, aiming to improve the fire performance of CFRP-strengthened concrete structures. The test results showed that the compressive strength of MOC remained nearly unchanged at 200°C and was about 52% of its room temperature strength at 350°C, but the adhesive failed completely at 400°C due to dehydration. Its flexural strength significantly decreased at 150°C, remained relatively stable between 150°C and 350°C, and then dropped completely at 400°C due to total dehydration. Increasing the thickness of the fireproof coating effectively improved fire resistance, but greater coating thickness also made the material more susceptible to spalling. Li [14] performed numerical simulations to compare the temperature distribution of unstrengthened RC slabs and CFRP-strengthened RC slabs without fire protection. The study also investigated how different thicknesses of intumescent fireproof coatings affected the fire resistance of CFRP-strengthened slabs under standard fire conditions. The findings revealed that the fire resistance of CFRP-strengthened slabs without any fire protection was extremely low (approximately 5 minutes), far below that of original unstrengthened RC slabs. However, in high-temperature fire scenarios, increasing the thickness of the fireproof coating significantly extended the fire resistance duration of CFRP-

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strengthened slabs. Xu et al. [15] carried out standard fire tests on five RC slabs: an unstrengthened slab, slabs strengthened with CFRP using either organic or inorganic adhesives, and slabs with or without fire protection measures. The study examined how adhesive type and fire protection strategies affected the failure modes, mid-span deformation, and fire resistance ratings of CFRP-strengthened slabs under elevated temperatures. The test results demonstrated that even without fire protection, slabs strengthened with CFRP bonded using inorganic adhesives still exhibited relatively good fire resistance. In contrast, slabs bonded with organic adhesives and lacking fire protection showed significantly poorer fire resistance.

3. Summary and Outlook

With the widespread use of reinforced concrete structures in modern buildings, their performance under fire conditions has increasingly become a focus of research. The fire resistance of reinforced concrete structures is influenced by various factors, particularly the choice of surface reinforcement materials and their bonding performance with the concrete substrate. As a lightweight, high-strength, and corrosion-resistant reinforcement material, carbon fiber fabric has been widely used to strengthen reinforced concrete structures due to its significant enhancement of mechanical properties. Under high-temperature fire conditions, carbon fiber fabric and its bonding interface with concrete are subject to severe thermal degradation, which adversely affects the structure's fire resistance. This paper summarizes recent research developments on the fire performance of reinforced concrete structures strengthened with carbon fiber fabric, analyzing its performance in beams, columns, slabs, and other structural components. Studies have shown that factors such as the proper application of fire-resistant coatings, sufficient thickness of the concrete cover, and appropriate load ratios play a crucial role in extending the fire resistance of strengthened components. Moreover, using inorganic adhesives instead of traditional organic ones can significantly improve the fire resistance of reinforced structures. Although the use of carbon fiber fabric has led to some improvements in the fire endurance of reinforced concrete structures, its effectiveness and fire resistance under high-temperature conditions are still limited by multiple factors, such as the thickness of fireproof coatings, the amount of reinforcement applied, and load levels. While significant progress has been made, numerous challenges remain in the study of fire performance of carbon fiber fabric–strengthened reinforced concrete structures. First, further research is needed on the long-term fire resistance of different types of fireproof coatings, adhesives, and their bonding performance with carbon fiber fabric. Second, the behavior of the interface between carbon fiber fabric and concrete under elevated temperatures requires more in-depth investigation to ensure more stable structural performance during fires. Finally, optimizing reinforcement strategies and material selection to enhance the load-bearing capacity and fire resistance of structures in extreme fire scenarios remains an important direction for future research.

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