Performance Optimization Strategy for Steel-Concrete Composite Structures: Post-Fire Load-Bearing Capacity and Deformation Control

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ABSTRACT Concrete-filled steel tube structures are widely used in industrial plants, large commercial buildings, infrastructure projects, antenna-supporting facilities, and electromagnetic-shielded spaces because of their strong mechanical performance and economic efficiency. Fire is a serious threat to structural safety. Under high temperatures, the load-bearing capacity and deformation control level of concrete-filled steel tube structures decrease significantly, while material strength loss, weakened interfacial bonding, and residual deformation develop simultaneously. These changes may not only reduce structural reliability but also affect the geometric stability required for antenna alignment and controlled electromagnetic environments.
This paper focuses on the post-fire performance of concrete-filled steel tube structures and systematically discusses how high-performance fiber-reinforced composite wrapping and constraint enhancement can mitigate material degradation and preserve load-bearing capacity under extreme thermal stress. By analyzing the relationships among temperature-induced material deterioration, residual deformation, stiffness reduction, and reinforcement strategies, the study evaluates load-bearing capacity attenuation and deformation control in fire-exposed composite systems. The proposed optimization strategy provides technical support for post-disaster assessment, structural strengthening, and the safe reuse of steel–concrete composite structures in industrial buildings and electromagnetic functional facilities.

INDEX TERMS concrete-filled steel tube, post-fire capacity, deformation control, antenna support structures, electromagnetic shielding

I. INTRODUCTION

With urbanization and increasingly demanding building requirements, concrete-filled steel tubular (CFST) structures, often reinforced by high-performance fiber-integrated composites derived from advanced engineering, are playing a growing role in various critical construction projects. This structural system relies on the external steel tubing to restrain the internally filled concrete, allowing the material properties to be fully utilized. It features high load-bearing capacity, good ductility, and convenient construction. However, fire is a highly destructive and sudden disaster, and the high-temperature effect can significantly impact the material properties and overall stress state of CFST structures. After a fire, the structure often experiences reduced load-bearing capacity, irreversible deformation, and a substantial decrease in stiffness. If not handled properly, this will only interfere with the normal use of the building; in severe cases, it can lead to gradual structural damage or even collapse.

II. ANALYSIS OF THE SIGNIFICANCE OF POST-FIRE PERFORMANCE DEGRADATION IN STEEL-CONCRETE COMPOSITE STRUCTURES

A. THE EFFECT OF FIRE ON THE LOAD-BEARING CAPACITY OF CONCRETE-FILLED STEEL TUBULAR STRUCTURES

The sustained high temperature caused by fire triggers irreversible changes in the mechanical properties of steel-concrete composite structures, necessitating the integration of advanced thermal barriers to maintain structural integrity. High-performance inorganic fibers, characterized by their superior heat resistance and tensile stability, provide a critical reinforcement layer that mitigates thermal degradation within these composite frameworks. Under the action of high temperature, the yield strength and elastic modulus of steel will be greatly reduced, and the concrete will suffer strength loss and internal damage due to water evaporation, aggregate cracking, decomposition of hydration products, etc. [1]. After the high temperature, even if there is no obvious damage on the surface of the structure, the load-bearing mode inside has undergone fundamental changes. After the high temperature, even if there is no obvious damage on the surface of the structure, the load-bearing mode inside has undergone fundamental changes. The axial compression load-bearing capacity, bending load-bearing capacity and shear capacity have all decreased to a certain extent, presenting critical challenges to the structural reliability and long-term stability [2].

B. HAZARDS OF UNCONTROLLED DEFORMATION TO STRUCTURAL SAFETY AND FUNCTIONALITY

During and after a fire, under the combined influence of thermal expansion, thermal creep and cooling contraction, steel-concrete composite structures are prone to irreversible residual deformation [3]. This uncontrolled deformation will cause the geometry of the components to deviate from the design requirements, destroy the structural force transmission path, and cause secondary stress concentration between components, accelerating the damage speed of the connection nodes. From the perspective of functional use, excessive structural deformation will directly endanger the normal use of the building, affect people's safety and comfort, and is a safety hazard that should not be underestimated [4].

C. THE VALUE OF POST-FIRE PERFORMANCE OPTIMIZATION RESEARCH FOR ENGINEERING DISASTER PREVENTION AND MITIGATION

Research on post-fire performance optimization of steel-concrete composite structures is of great theoretical and practical significance for improving the disaster prevention and mitigation capabilities of engineering structures. From a macro perspective, a systematic understanding of the performance degradation mechanism of structures after fire can lead to the formation of scientific, reasonable and effective post-disaster assessment methods and repair criteria, providing support for engineering decision-making [5]. From a micro perspective, targeted improvement measures can effectively delay the process of structural performance degradation, reduce the risk of secondary disasters, reduce economic losses, ensure people's safety, and promote a substantial improvement in the disaster prevention and mitigation capabilities of the entire construction industry [6].

III. MAIN PROBLEMS OF POST-FIRE LOAD-BEARING AND DEFORMATION OF STEEL-CONCRETE COMPOSITE STRUCTURES

A. MECHANISM OF MATERIAL MECHANICAL PROPERTY DEGRADATION AFTER HIGH TEMPERATURE

After a high-temperature fire, the mechanical properties of the various materials contained in the steel-concrete composite structure will decrease significantly and this decrease is irreversible. High temperature changes the microstructure of the steel crystal in the outer steel pipe, increases the dislocation density, significantly reduces the yield strength and ultimate tensile strength, and the elastic modulus decreases continuously with the increase of temperature [7]. After exposure to temperatures exceeding 600°C, the mechanical properties of the steel undergo severe degradation. Even upon cooling to room temperature, the yield strength only recovers to approximately 65–80% of its original value. This partial recovery is attributed to irreversible changes in the steel's crystalline microstructure, such as increased dislocation density and grain coarsening, which prevent the material from returning to its pre-fire metallurgical state. Due to the high temperature, the free water and bound water in the inner concrete evaporate in large quantities, and there is thermal incompatibility between the aggregate and the cement paste, which causes the development of internal microcracks. Hydration products such as calcium silicate decompose at high temperature, resulting in a decrease in both the compressive strength and elastic modulus of the concrete [8]. In order to more intuitively reflect the degree of influence of high temperature on the mechanical properties of the main materials, the following table summarizes the changes in the key performance indicators of steel and concrete in different temperature ranges.

B. POST-FIRE STRUCTURAL BEARING CAPACITY ATTENUATION AND UNEVEN DISTRIBUTION

The reduction in the load-bearing capacity of steel-concrete composite structures after a fire is a systemic problem. It manifests in the absolute reduction of the load-bearing capacity of the entire structure and also in the serious imbalance of the load-bearing capacity distribution in the structural system. From the perspective of components, the temperature distribution of the cross sections of components with different degrees of fire exposure is also quite different, resulting in different remaining load-bearing capacities of each component [9]. Components close to the fire source or with a large exposed area have a large temperature gradient, heavy material damage, and rapid load-bearing capacity reduction; components inside the building or with protection have basically unchanged load-bearing capacity. While protected or internal components may appear less affected, they are still subject to secondary thermal stress and capacity reduction caused by heat conduction through the continuous steel skin and the global thermal expansion of the structural frame, which can redistribute internal forces across the entire system. Such uneven distribution of load-bearing capacity will cause some components to bear more than the maximum internal force allowed by the design when the structure is reloaded, creating new weak points. From the perspective of the overall structure, due to the local concentration of load-bearing capacity and the reduction of static indeterminate redundancy of the structure, local components will quickly fail, resulting in the collapse of the entire system [10]. In order to further quantify the degree of load-bearing capacity reduction of components under different fire conditions, the following table compares and analyzes the remaining load-bearing capacity level of steel-concrete composite columns under typical fire conditions

TABLE 1. Comparison of mechanical property degradation of steel and concrete at different temperatures

Temperature Range (°C)	Steel Yield Strength Retention Rate (%)	Steel Elastic Modulus Retention Rate (%)	Concrete Compressive Strength Retention Rate (%)	Concrete Elastic Modulus Retention Rate (%)
Normal temperature (20)	100	100	100	100
200	95–100	90–95	90–95	85–90
400	75–85	70–80	70–80	65–75
600	40–55	45–60	45–60	40–55
800	15–25	20–30	20–30	15–25
Cool to room temperature	65–80	75–85	55–70	50–65

(Table 2).

C. ACCUMULATED RESIDUAL DEFORMATION LEADS TO A DECREASE IN THE OVERALL STIFFNESS OF THE STRUCTURE

The accumulation of residual deformation has become another major problem after the fire of steel-concrete composite structures. The cause is the creep of the material at high temperature, thermal expansion and contraction, and the strain incompatibility resulting from the thermal expansion mismatch between the steel and concrete. During the fire, the structure expands due to heat, and the components generate thermal stress and forced deformation under constraints. During the cooling stage, the material shrinks and residual thermal stress is superimposed, resulting in many irreversible permanent deformations remaining in the structure [11]. As the residual deformation continues to accumulate, the initial geometric defects of the components are aggravated, the effective force-bearing area of the cross section is reduced, the center of structural stiffness shifts, and the overall lateral stiffness and vertical stiffness decrease to a certain extent. The reduction in stiffness will cause the structure to produce greater deformation under normal service loads, and will also cause the structure's natural vibration period to be longer, resulting in a worse dynamic response under earthquake or wind loads [12]. In order to more clearly present the specific impact of residual deformation accumulation on the overall stiffness of the structure under different fire conditions, Table 3 below systematically sorts out and compares the degradation of the main stiffness indicators of steel-concrete composite structures under typical working conditions.

IV. POST-FIRE PERFORMANCE OPTIMIZATION STRATEGIES FOR STEEL-CONCRETE COMPOSITE STRUCTURES

A. LOAD-BEARING CAPACITY ENHANCEMENT SCHEME BASED ON MATERIAL PERFORMANCE REPAIR

Effective repair of material properties is the basic work to restore the load-bearing capacity of steel-concrete composite structures after fire. Different repair measures should be formulated according to the deterioration characteristics of steel pipes and concrete. For the repair of outer steel pipes, non-destructive testing should be used to comprehensively evaluate the damaged steel pipes in order to accurately identify the damage status and remaining strength of each section. For parts with local buckling deformation and cross-sectional weakening, steel plates should be welded to strengthen [13]. For parts with local buckling deformation and cross-sectional weakening, steel plates should be welded to strengthen the section to restore the lost effective load-bearing area of the material. Special attention should be paid to the risk of brittle fracture in places where high temperature reduces the toughness of steel. When it is necessary to replace the severely damaged parts locally, the continuity and reliability of the entire structure should also be considered. When repairing the inner concrete, the focus should be on solving the problem of internal microcrack expansion and strength reduction caused by high temperature. Modified epoxy resin or cement-based grouting material should be injected into the cracks inside the concrete using chemical grouting to fill the cracks, restore the continuity of the material and improve the integrity and compressive strength of the concrete [14].

B. DEFORMATION CONTROL METHODS FOR STRUCTURAL STRENGTHENING AND CONSTRAINT ENHANCEMENT

Deformation control is one of the main objectives of improving the post-fire performance of steel-concrete composite structures. Its realization depends on the combined efforts of constraint strengthening and structural reinforcement, aiming to arrest further deformation development, restore the structural load-bearing capacity, and compensate for the loss of overall stiffness . In terms of constraint strengthening, reinforcement with outer sleeve is a better deformation control method. Adding new steel pipes or steel sleeves to the outer wall of the original damaged steel pipe can significantly improve the lateral constraint force on the internal concrete, reduce the lateral expansion of the concrete, and prevent the deformation of the component from continuing to develop [15]. The number and spacing of the sleeves should be determined according to the damage of the component and the load-bearing requirements to ensure the uniformity and effectiveness of the constraint effect. In terms of constraint strengthening, carbon fiber reinforced composite winding technology should be applied to the entire component. This enhances the circumferential confinement stiffness, thereby improving the post-fire deformation performance and overall structural stability by restoring the synergistic action between the steel and concrete. It has the characteristics of high strength and low density, which can improve the circumferential constraint stiffness of the component, improve the deformation performance of the component after fire, and have little impact

TABLE 2. Comparison of Remaining Bearing Capacity of Concrete-Concrete Composite Steel Tube Columns under Different Fire Conditions

Fire-affected conditions	Fire exposure time (min)	Maximum temperature (°C)	Axial compression bearing capacity retention rate (%)	Flexural bearing capacity retention rate (%)	Shear capacity retention rate (%)
Unexposed to fire (control group)	0	20	100	100	100
Minor fire damage	30	400–500	80–90	78–88	82–90
Moderately affected by fire	60	600–700	60–75	58–72	62–75
Severe fire	90	750–850	40–55	38–52	42–56
Extremely severe fire	120 or more	850 and above	20–35	18–32	22–36

TABLE 3. Comparison of stiffness degradation of steel-concrete composite structures under different fire exposure levels

Fire extent	Axial residual deformation rate (%)	Lateral residual displacement rate (%)	Lateral stiffness retention rate (%)	Vertical stiffness retention rate (%)	Natural period change rate (%)
Unexposed to fire (control group)	0	0	100	100	0
Minor fire	0.1–0.3	0.2–0.5	88–95	90–96	+5–+12
Moderately affected by fire	0.5–1.0	0.8–1.5	70–82	72–85	+18–+30
Severe fire	1.2–2.0	1.8–3.0	50–65	52–68	+35–+50
Extremely severe fire	2.5 or above	3.5 or above	30–45	32–48	+55 and above

on the original structure during construction. For places where deformation is concentrated due to reduced load-bearing capacity and reduced stiffness, corresponding local reinforcement measures should be adopted. For components that exhibit significant lateral bending or axial compression deformation, additional support systems or diagonal braces can be installed to redistribute the internal forces of the structure, reduce the stress level of weak components, and thus effectively control the development of deformation.

C. COMPREHENSIVE OPTIMIZATION STRATEGY DRIVEN BY FULL-PROCESS MONITORING AND EVALUATION

To maintain the good performance of concrete-filled steel tubular structures after a fire, a comprehensive monitoring and evaluation system must be established. Data should guide repair decisions, continuously track the performance recovery process, and promptly issue warnings about potential safety hazards. In the early stages of a fire, a systematic on-site investigation and testing of the damaged structure should be conducted, employing methods such as visual inspection, ultrasonic testing, infrared thermography, and core drilling to comprehensively understand the damage patterns, material degradation, and residual deformation distribution of various parts of the structure. Based on this, a finite element analysis model based on measured data should be established to qualitatively evaluate the load-bearing capacity and deformation of the post-fire structure, providing a basis for the design of subsequent repair and reinforcement schemes and avoiding errors in repair direction due to subjective assumptions. During the repair and reinforcement process, continuous monitoring of key structural components is essential, primarily observing strain changes in weak load-bearing areas, nodal displacements, and crack development. By deploying strain gauges, accelerometers, and crack detectors at key structural nodes, the structural response during repair was monitored to detect anomalies early and make improvements, ensuring the safe and orderly progress of the repair project and preventing new safety hazards caused by construction interference. Based on the above three aspects of analysis, to clearly present the overall impact of fire on the performance of various layers of the steel-concrete composite structure, Table 4 systematically compares the structural performance before and after the fire from five dimensions: steel performance, concrete performance, interface state, load-bearing capacity, and deformation stiffness.

TABLE 4. Comparison of the performance of steel-concrete composite structures before and after fire

Comparison Dimensions	Before the fire	After the fire
Mechanical properties of steel	Yield strength intact (100%), normal elastic modulus, good toughness, and sufficient ductility.	Yield strength remains at 40–80%, elastic modulus decreases by 15–55%, crystal structure changes, and risk of brittleness increases.
Mechanical properties of concrete	The compressive strength is intact (100%), the elastic modulus is normal, the interior is dense, and there are no cracks.	The compressive strength is retained at 45–70% due to the decomposition of hydration products, the expansion of internal microcracks in the aggregate, and a decrease in overall integrity.
Steel pipe-concrete interface state	The bonding force is intact, the constraint effect is sufficient, and the load transfer is normal.	Differences in thermal expansion significantly weaken the interfacial debonding constraint and obstruct the load transfer path.
Structural bearing capacity	Axial compression, bending, and shear strength all meet design values; load distribution is uniform with no weak points.	The bearing capacity in all three directions decreased to varying degrees, resulting in uneven load distribution. Under extreme conditions of local overloading, this led to a series of collapses.
Deformation and Stiffness	Deformation is recoverable, residual deformation is minimal, lateral stiffness/vertical stiffness is normal, and natural vibration period is normal.	Residual deformation is irreversible, and the cumulative effect reduces lateral stiffness by 5–70%, lengthens the natural period, and worsens the dynamic response.

V. CONCLUSION

The post-fire performance degradation of concrete-filled steel tubular (CFST) structures results from multi-level material and structural compromises, which can be mitigated through the incorporation of high-performance composites designed to maintain mechanical stability under extreme thermal stress. These advanced technical provide a multi-dimensional reinforcement network that preserves the load-bearing capacity and structural integrity of the composite components following high-temperature exposure. This paper systematically discusses post-fire performance degradation from two aspects: improving post-fire load-bearing capacity and controlling deformation, and proposes corresponding improvement methods. The study found that a synergistic approach of improving material properties, strengthening structural constraints, and conducting comprehensive monitoring and evaluation can effectively restore the load-bearing capacity of CFST structures after fire, control structural deformation, and ensure safe building use. Future research should further explore the post-fire degradation mechanisms of structural components, integrating advanced fiber-matrix interface analysis into evaluation criteria and repair technology systems to provide robust theoretical support for disaster prevention in building engineering. These restoration strategies utilize high-tenacity weaving architectures to restore the mechanical integrity of compromised structures, ensuring long-term stability and resilience against thermal damage.

AUTHOR CONTRIBUTIONS

Conceptualization –Li Weiwei and Hou Wenkang; methodology – Li Weiwei and Hou Wenkang; investigation – Li Weiwei and Hou Wenkang; writing-original draft preparation – Li Weiwei and Hou Wenkang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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