

Study on Mechanical Properties and Application of FRP Confined Concrete-Filled Steel Tube Columns

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Abstract. With the increasing demand for high performance and high durability materials in civil engineering, traditional structural materials such as concrete columns and steel columns face challenges. Concrete-filled steel tube (CFST) columns combine the advantages of both, but are susceptible to corrosion. This study focuses on the mechanical properties and application prospects of fiber reinforced polymer (FRP) confined CFST columns. Firstly, the effect of FRP confinement on the compressive strength, ductility and toughness, crack resistance and shear resistance of CFST columns is discussed. Secondly, through theoretical analysis, performance exploration and practical application cases, the broad application prospects of FRP confined CFST columns in high-rise buildings, bridge engineering and reinforcement are verified. The findings point to a new avenue for technical advancement in the field of civil engineering since the double confinement of FRP greatly increases the bearing capacity and stability of CFST columns. Finally, the study points out that the future needs to deepen the research on the interface bond performance, long-term durability and optimal design of FRP, steel pipe and concrete, so as to encourage the widespread use of FRP constraint technology in civil engineering and contribute to the creation of a smarter, safer, and more environmentally friendly future city.

Keywords: FRP confined concrete-filled steel tube column; Mechanical properties; Compressive strength; Ductility.

1. Introduction

With the continuous progress in the field of civil engineering, the demand for structural materials with high performance and high durability is increasingly urgent. Traditional structural forms, such as concrete column and steel column, although each has its own unique advantages, but in the long-term use process, often face durability and safety challenges. The concrete-filled steel tube (CFST) column is a novel composite structure that effectively blends the benefits of steel and concrete. This enhances the structure's ductility and seismic performance while also increasing bearing capacity. Compared with simple concrete column, CFST column significantly improves its compressive strength and crack resistance by constrains the core concrete with steel tube. Compared with steel columns, the presence of outer concrete effectively enhances the fire resistance and corrosion resistance of the structure [1]. However, despite the excellent performance of CFST columns, they are still susceptible to corrosion during long-term service, which reduces the durability and the structure's safety.

In recent years, because of its great strength, low weight, and resistance to corrosion, fiber reinforced polymer (FRP) has found widespread application in the field of civil engineering. The term FRP refers to a high-performance composite material created by blending fiber and matrix materials in specific proportions. There are several different kinds of FRP, such as glass fiber reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP), and aramid fiber reinforced plastic (AFRP). These different types of FRP materials have their own characteristics, such as GFRP has good insulation and corrosion resistance, CFRP has extremely high strength and stiffness, and AFRP is known for its excellent fatigue resistance and impact resistance. It is these diverse properties that enable FRP materials to meet the needs of different engineering fields. By applying FRP to the outer restraint of concrete-filled steel tubular column, it can not only effectively isolate the erosion of the external



environment on the steel pipe, but also further provide additional restraint effect and significantly improve the mechanical properties of the structure. As a new type of composite structure, FRP confined CFST column has significantly improved its compressive strength, durability, ductility, crack resistance and shear resistance, providing a new direction for technological innovation in the field of civil engineering [2].

The objective of this research is to investigate the impact of FRP constraints on the effectiveness of concrete-filled steel tubular columns is examined, along with an explanation of how these constraints enhance the mechanical properties of such columns. This is achieved through theoretical analysis, performance investigation, and real-world application. Through a comprehensive analysis of the mechanical characteristics of CFST columns that are reinforced with FRP, this study also looks forward to its application in high-rise buildings, seismic design, bridge engineering and reinforcement and other fields, aiming at contributing to the technical progress in the field of civil engineering.

2. Mechanical Properties

2.1. Compressive Strength Significantly Improved

The improvement of compressive strength of FRP confined CFST columns is one of the most remarkable advantages in its mechanical properties, which completely subverts the load-bearing limit of traditional materials. The FRP confined CFST column is a novel structural system that employs tightly wrapped FRP material around the exterior of the CFST column, resulting in a dual restraint effect. This innovative configuration not only combines the high load-bearing capacity and excellent ductility of CFST, but also fully exploits the exceptional properties of FRP materials, including their lightweight nature, high strength, corrosion resistance, and fatigue resistance. The application of FRP wrapping significantly improves the compressive strength and ductility of concrete-filled steel tubular columns, giving this composite material exceptional mechanical properties even in extreme loading scenarios. Research conducted by Yu et al. [3] indicates that the load-bearing capacity of FRP confined CFST columns is primarily influenced by the constraint effect coefficient of FRP on CFST, the compressive strength of the unconstrained concrete, and the thickness of the steel tube. Utilizing elastic theory and equivalent cross-section analysis, the research team developed a formula for calculating bearing capacity, which was validated against existing test data, showing strong agreement.

$$A_{ce} = A_c + \alpha_E A_s \quad (1)$$

$$N_u = A_{ce} f_{co} (1 + 1.31 \xi_f) \quad (2)$$

where A_{ce} is the area of the equivalent concrete, A_c is section area of concrete, α_E is ratio of elastic modulus of steel pipe to concrete, A_s is steel area, N_u is bearing capacity of concrete columns restrained by FRP, f_{co} is compressive strength of concrete cylinder, and ξ_f is restraining effect coefficient of FRP on concrete.

This discovery highlights the considerable impact of FRP confinement on the compressive strength of concrete-filled steel tubular columns. Under the same conditions, the ultimate bearing capacity of FRP confined CFST column is much higher than that of ordinary CFST column, especially under the high constraint effect coefficient, the bearing capacity improvement effect is more significant. While traditional concrete and steel have a natural upper limit in terms of compressive strength, FRP confined CFST columns achieve a significant increase in compressive strength through material composition and structural innovation. The encapsulation of FRP materials effectively limits the transverse expansion of concrete in the steel pipe, making the core concrete in a three-way compression state, thus greatly improving its compressive strength and deformation ability [4]. This

dual restraint system enhances the load-bearing ability of the columns while also greatly increasing their ductility and capacity for energy dissipation, which makes the FRP confined CFST columns exhibit better performance under extreme loads such as earthquake resistance and wind resistance. Smaller section sizes can withstand greater loads, thereby saving material and reducing structural weight while ensuring structural stability and safety. This breakthrough not only conserves a significant amount of resources in engineering design, but also provides designers with greater design freedom and can respond more flexibly to various complex design needs, bringing unprecedented innovation opportunities for modern engineering design. In addition, the lightweight nature of FRP material also reduces transportation and installation costs, which brings a significant improvement in project economics, while its good corrosion resistance and durability also ensure the long life of the structure and low maintenance costs, providing a strong support for the sustainable development of the building.

2.2. Increased Ductility and Toughness

The improvement of ductility and toughness of FRP confined CFST columns shows a revolutionary leap in their structural properties. In contemporary construction and bridge engineering, the ductility and toughness of structures are crucial elements for maintaining stability and safety when subjected to extreme loads. CFST are a type of high-performance structural material that has gained popularity in the construction of skyscrapers, bridges, and other infrastructure. This is due to their ability to combine the compressive strength of steel pipes with the compressive properties of concrete. However, when the CFST member reaches its ultimate bearing capacity, the local buckling of the steel pipe often leads to a sharp decline in mechanical properties [1]. In order to overcome this defect, FRP has been introduced in recent years due to its lightweight and high strength properties, forming FRP confined CFST column, which significantly improves the ductility and toughness of members. Among them, ductility is the ability of a structure to produce large plastic deformation without significantly reducing its bearing capacity after reaching its maximum bearing capacity. The research of Zhang et al. [5] shows that the ductility of CFST columns has been significantly improved through the confinement of FRP materials. Specifically, CFST column specimens with CFRP confinement show the highest ultimate bearing capacity and the best ductility, and their ultimate strain increases significantly. The improvement of ductility is due to the dual restraint effect of FRP material on steel pipe and core concrete, which effectively delays the local buckling of steel pipe, thus improving the deformation ability of the overall structure. Toughness is the ability of a structure to absorb energy without sudden failure when subjected to impact or cyclic loads. The introduction of FRP constraints not only improves the ductility of CFST columns, but also significantly enhances their toughness. Under cyclic loads or dynamic loads such as earthquakes, the confinement effect of FRP can distribute and dissipate energy more effectively, avoiding sudden failure of structures under extreme loads. In particular, the BFRP constrained CFST column specimens show better ductility and toughness than GFRP specimens under the same constraint strength, which further verifies the difference of influence of different FRP materials on CFST column properties. The study of Zhang Yitian et al. verified the effect of FRP confinement on the ductility and toughness of concrete-filled steel tubular columns through detailed axial compression tests. The test results show that the CFST column specimens with CFRP confinement have excellent performance in ultimate bearing capacity and ductility. Based on the experimental results, they put forward a formula for calculating the axial bearing capacity of CFST column, which is in good agreement with the experimental results and other research data, and provides a reliable theoretical basis for the application of CFST column in practical engineering.

2.3. Optimization of Crack and Shear Resistance

In the discipline of civil engineering, the development and application of new composite structural materials has always been an important direction to improve the safety and durability of building structures. As an innovative composite structure, FRP confined CFST column has set a new standard for the overall stability and safety of building structures due to its excellent cracking and shear

resistance. Tian [6] considered that the design concept of FRP confined CFST column cleverly combines high-strength and high-modulus FRP material with traditional CFST structure, and realizes the double constraint on steel tube and concrete through the tight wrapping of FRP. This design markedly enhances the stiffness and load-bearing capacity of the components, thereby offering a more robust support system for the structure to endure lateral forces, including those generated by seismic activity. Under extreme loads, the restraining effect of FRP is like a solid armor, which effectively absorbs the impact energy and evenly disperses it to the entire structural system, thus avoiding the damage caused by local stress concentration. The exceptional strength properties of FRP facilitate a secure adhesion to the steel pipe, thereby mitigating the risk of local buckling under pressure. This, in turn, ensures the effective confinement of the internal concrete by the steel pipe. Concurrently, the application of FRP on concrete restricts the lateral expansion of the concrete substrate and postpones the initiation and progression of cracking. This dual restraint mechanism not only enhances the crack resistance of the component substantially but also contributes to the overall durability of the structure. Regarding shear resistance, the interaction among FRP, steel pipe, and concrete is pivotal. The high modulus of FRP enhances the comprehensive rigidity of the structure and makes the structure more stable when subjected to shear forces. At the same time, the close adhesion of FRP and steel pipe forms a strong shear transfer interface, which effectively improves the shear strength of the member. This combined effect makes FRP confined CFST columns exhibit higher resistance and ductility in the face of shear failure, ensuring the overall safety of the structure under extreme conditions. In summary, the notable enhancement in crack resistance and shear resistance of FRP confined CFST columns offers a robust assurance for the overall safety and longevity of structural systems in buildings.

2.4. Deformation Control and Stiffness Enhancement

In the structural design of CFST columns, the regulation of deformation is crucial for maintaining the overall safety of the structure. Due to the significant difference in material properties between steel pipe and concrete and the variability of the use environment, the column is prone to buckling and deformation under axial pressure. This phenomenon is particularly obvious in specimens with large length-diameter ratio. As pointed out by Wang et al. [7], specimens with increased length-diameter ratio are more likely to suffer stable failure under axial pressure. To address this issue effectively, FRP confinement technology has been developed, offering an innovative approach to the deformation control of CFST columns. By pasting FRP sheet on the outer steel pipe, a strong and effective restraint layer can be formed, which can significantly improve the anti-buckling ability of the column. This restraining effect extends beyond merely constraining the deformation of the column; more significantly, it offers sufficient binding force to ensure the stability of the column without augmenting the overall weight of the structure. The utilization of this technology capitalizes on the mechanical characteristics of FRP materials, thereby facilitating the efficient reinforcement of CFST columns. Li [8] further elucidated the beneficial effects of the FRP confinement layer on the structural properties of these columns. The study shows that the FRP confinement layer can significantly improve the hysteretic energy dissipation and damping characteristics of concrete-filled steel tubular columns, and thus enhance their seismic performance. This finding is of great significance for improving the safety of structures under dynamic loads such as earthquakes. In addition to its role in deformation control, FRP confinement technology markedly increases the stiffness of CFST columns, which in turn enhances the load-bearing capacity of the overall structure. Under axial pressure, the stiffness of CFST column is mainly determined by the combined effect of steel tube and concrete. However, due to the complex interaction between the two materials and the nonlinear characteristics of the material itself, the stiffness of the column is often difficult to meet the design expectations in practical use. The application of FRP restraint technology enhances the combination effect between steel pipe and concrete by forming an effective restraint layer on the outer steel pipe. This reinforcement not only improves the overall stiffness of the column, but also improves its mechanical performance. According to the analysis of Fan [9], the fourth strength theory and the failure criterion of concrete under the three-way stress state are adopted for calculation, and the discrepancy between

the theoretical findings and the results reported in the literature is minimal. This result substantiates the efficacy of FRP confinement technology in enhancing the load-bearing capacity of CFST columns. In addition, the experimental results also show that the number and arrangement of FRP confinement layers have an important effect on the strengthening effect. In practical applications, it is essential to strategically determine the quantity and configuration of FRP restraint layers in accordance with the particular environmental conditions and load specifications. For example, the load bearing capacity and stiffness of the column can be further improved by increasing the number of FRP confinement layers or by adopting a more efficient arrangement.

The excellent improvement of FRP confined CFST columns in compressive strength, ductility, crack resistance, shear resistance, deformation control and stiffness has not only brought revolutionary changes to the field of structural engineering, but also provided unlimited innovation possibilities for architecture and engineering design. As advancements in FRP material technology continue and application research becomes more comprehensive, the performance of FRP-confined CFST columns is expected to be further enhanced. This improvement will offer substantial material support for the development and safeguarding of future urban environments.

3. Applied Research

3.1. Building Structure

In the in-depth exploration of the latest progress and application of building structure reinforcement technology, FRP materials with its excellent mechanical properties, excellent corrosion resistance and construction convenience, has become the focus of modern civil engineering research and practice, especially in the maintenance and reinforcement of old civil buildings show significant advantages. Taking the reinforcement project of Texas Hamilton Hotel in the United States as an example, in view of the decline in bearing capacity caused by long-term service of some of its structural columns, researchers successfully implemented the FRP circumferential winding reinforcement strategy through precise mechanical analysis and design [10]. This technology not only significantly enhances the compressive and shear resistance of the columns, but also effectively improves the stability of the overall structure, providing a scientific basis and practical example for the protection and restoration of historical buildings. Similarly, in the Hilton Hotel at Bergstroms Airport in the United States, in the face of the strict requirements for the safety of the building structure due to the high density of people, engineers also adopted FRP strengthening technology to systematically strengthen the key bearing columns. This approach not only guarantees the safety and reliability of the hotel infrastructure but also assesses the efficacy and practicality of FRP strengthening technology within intricate engineering contexts, achieved through meticulous construction techniques and rigorous quality assurance protocols. In Japan, the application of FRP strengthening technology has reached an unprecedented breadth and depth. According to the statistics of Wu [11], FRP materials account for 45% and 40% of general building and bridge reinforcement projects in China, respectively, which shows its wide application value in improving the safety performance of building structures. CFST columns play an important role in high-rise buildings, long-span Bridges and other engineering fields because of their unique mechanical characteristics. However, with the increase of service time, the problem of its performance degradation has become increasingly prominent. Under this background, the technology of FRP confinement has become an effective way to enhance the load-bearing capacity and seismic performance of CFST columns with its unique advantages. Through in-depth research on the strengthening mechanism, optimization design method, improvement of construction technology and evaluation of long-term performance of FRP confined CFST columns, it can not only provide scientific basis for engineering practice, but also promote technological innovation and development in the field of civil engineering.

3.2. Bridge Structure

In the field of bridge engineering, FRP confined CFST columns, as a new structural form, are gradually becoming the key technology to enhancing the load-bearing capacity and seismic resilience of bridges. The utilization of this technology not only improves the safety of bridge structure, but also prolongs the service life of bridge, and injects new vitality into modern bridge engineering. In recent years, researchers both domestically and internationally have conducted a range of theoretical and experimental investigations concerning FRP confined CFST structures, and have been applied in practical projects. Taking the northeast section of Nanjing Ryuyue Expressway as an example, the project adopts FRP constrained CFST columns as the pier structure [12]. The pier is located in the central dividing zone of Ninglian Expressway and its size is strictly limited. By using FRP to restrain CFST columns, the section size and construction period are successfully reduced, and the bearing capacity and seismic performance of piers are significantly improved. In the specific application, as shown in Fig. 1, the FRP material is tightly wound around the outside of the steel pipe, forming a tight whole with the concrete inside the steel pipe. This structural form can utilize to the fullest extent to the respective advantages of FRP and steel pipe when bearing external loads, forming a synergistic effect, thereby improving the stability and safety of the overall structure. In addition, in other bridge projects, such as the bridge tower of large bridge across the river and sea, bridge pier of important traffic nodes, FRP constrained concrete filled steel tube columns have also been widely used. These projects have demonstrated the superior performance of FRP confined CFST columns in practical applications, thereby establishing a robust foundation for their broader adoption and implementation within the domain of bridge engineering.



Figure 1. The process of FRP pasting of the concrete filled FRP-steel composite tube pier for Chengqiao hinge [13]

3.3. Underground Structure

FRP confined CFST columns also play an important role in tunnel and subway projects. During tunneling, temporary or permanent support structures are needed to maintain the stability of the caverns. FRP confined CFST columns are the best choice for tunnel supporting structures because of their substantial load-bearing capacity and favorable seismic performance. They can not only effectively resist the surrounding rock pressure, but also maintain the stability of the structure when natural disasters such as earthquakes occur, and guarantee the protection of personnel and vehicles in the tunnel. At the same time, in the construction of underground Spaces such as subway stations, FRP confined CFST columns are often used as load-bearing components in station halls, platforms and other areas to enhance the stability and safety of the overall structure. For example, New York in the United States has adopted FRP in the roof and platform column structures of many subway stations.

4. Conclusion

This paper examines the notable enhancement of mechanical properties in CFST columns confined with FRP. Through a combination of theoretical analysis and experimental validation, it demonstrates that FRP confinement substantially improves the compressive strength, ductility, toughness, as well as the crack and shear characteristics of concrete-filled steel tubular columns. Furthermore, it effectively regulates structural deformation and increases stiffness. Specifically, the dual restraint effect of FRP not only limits the localized buckling phenomenon in steel pipe and the transverse expansion of concrete, but also significantly improves the load-bearing capacity and stability of the member under extreme loads. In addition, the lightweight, high strength, corrosion resistance and other characteristics of FRP materials provide a strong guarantee for the long-term service of the structure.

In the application research of FRP confined CFST column in practical engineering, case analysis show that FRP confined technology has shown broad application prospects in the fields of building structure, bridge structure and underground structure. In the aspects of old building reinforcement, high-rise building support, bridge pier and tunnel support, FRP confined CFST column has become an important means to improve structural safety and durability due to its excellent mechanical properties and economic benefits. These application examples not only verify the effectiveness of FRP constraint technology, but also provide valuable reference for future engineering practice.

Although remarkable achievements have been made in the physical characteristics of materials and applications of FRP confined CFST columns, there are still some shortcomings in the current research. First of all, the research on the interface bond performance between FRP and steel pipe and concrete is not deep enough, which is directly related to the effectiveness and durability of the constraint effect. Second, the durability of FRP materials under long-term service conditions and their sensitivity to environmental factors still need to be further explored to guarantee the security and dependability of the structure throughout its life cycle. Furthermore, as the construction industry continues to evolve, there is a growing diversification in the demand for new structural materials. Consequently, optimizing the design parameters and construction techniques of FRP confined CFST columns in accordance with specific engineering requirements represents a significant area for future research. With advancements in the field of materials science, structural engineering and computer simulation technology, the performance of FRP confined CFST columns will be further optimized and improved. Through interdisciplinary cooperative research, more mysteries about the mechanism of FRP constraint can be revealed, and the extensive application of FRP constraint technology in the field of civil engineering can be promoted, contributing to the construction of a safer, green and intelligent future city.

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