

Progress of Research on Fire-resistant Steel in Civil Engineering

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Abstract: With advancements in construction technology, steel structures have become increasingly prevalent in industrial and civil buildings due to their lightweight nature, high strength, and excellent seismic resistance. However, the strength and load-bearing capacity of standard structural steel decrease under high temperatures, resulting in potential damage or even collapse of steel structures during fires. Consequently, these structures often require enhancements such as fire-resistant coatings or panels to improve their fire-resistance capacity. Presently, most countries utilize fire-resistant steel construction, which exhibits superior high-temperature mechanical properties compared to ordinary structural steel, thereby enhancing the fire safety of these structures. This paper presents an overview of the global progress in fire-resistant steel research, discusses the high-temperature mechanical properties of fire-resistant steel and the impact of alloying elements, and illustrates its application in building structural frameworks, fire-resistant compartments, and bridge projects. The information provided herein aims to contribute valuable references for civil engineering practices and future research.

Keywords: Fire-resistant steel, Fire resistance, High-temperature mechanical properties, Application

1. Introduction

In the contemporary construction sector, the continually evolving and innovative building construction technology has increasingly been utilizing steel structures in industrial and civil buildings. The primary reason for this widespread application is the notable advantages of steel structures. These advantages include a relatively lightweight structure that, under the same mechanical performance requirements, can effectively reduce the overall weight of the building compared to traditional concrete structures, thus facilitating construction and foundation design. The material's high strength can tolerate substantial loads, providing robust structural support for large-span, high-rise, and other intricately formed constructions. Additionally, steel structures possess excellent seismic performance due to their ductility and deformability, which effectively absorb and dissipate seismic energy during earthquakes and other natural disasters. This safeguards the overall stability and safety of the building structure.

However, it is crucial to note that ordinary structural steel has inherent flaws, such as a sharp deterioration in its strength characteristics and load-bearing capacity as the ambient temperature rises. In the event of a fire, the high-temperature heat generated by the fire causes a rapid decay in the

mechanical properties of ordinary structural steel. This results in a reduction in the structure's overall rigidity and an increase in deformation, which can easily trigger local or even total destruction of the building structure. In severe cases, it can even lead to the collapse of the building, resulting in incalculable loss of life and property. Traditional fire protection measures for ordinary structural steel construction mainly involve spraying fireproof coating on the steel surface or installing fireproofing panels, which are passive fire protection methods. These measures aim to maintain the steel's low-temperature state for a certain period by preventing heat transfer to the steel interior, thus ensuring the steel can still bear a certain load during a fire and enhancing the building structure's overall fire resistance.

In recent years, the global construction industry has witnessed an emerging trend of using fire-resistant steel. Compared to ordinary structural steel, fire-resistant steel exhibits unique advantages in high-temperature mechanical properties. It maintains relatively high strength and stability at high temperatures, and the rate of decay in its mechanical properties is significantly less than that of ordinary structural steel. This attribute fundamentally optimizes the fire-resistant performance of steel buildings, significantly enhancing the overall safety and reliability of steel buildings during a fire. It also provides a more robust guarantee for people's evacuation, fire rescue operations, and the reduction of fire losses.

This paper aims to explore the research and development process of fire-resistant steel in today's international construction field. It will focus on a detailed discussion on the law of change in the mechanical properties of fire-resistant steel at high temperatures. Additionally, it will perform an in-depth analysis of the key role played by alloying elements in the microstructure and macro-performance of fire-resistant steel. Through the actual engineering application of the building structural framework system, the use of fireproof compartment materials, and bridge engineering construction, this paper aims to provide a comprehensive description of the characteristics and advantages of fire-resistant steel in different scenarios. The goal is to provide practical guidance for professional practice activities in the field of civil engineering, serve as a reference basis, and lay a solid theoretical foundation for future in-depth research, drawing on practical experience.

2. The Concept of Fire-resistant Steel

Fire-resistant steel, a derivative of ordinary steel, is created through various processes. The production process involves the addition of alloying elements, multiple processing steps, precise control of rolling, and optimization of the cooling process, resulting in a product that is characterized by its low alloy content, high strength, and excellent refractory properties.

Fire-resistant steel is commonly used in high-temperature and high-pressure environments due to its exceptional resistance to extreme temperatures, pressure, and corrosion, resulting in a long service life. Most fire-resistant steels are alloyed to achieve these properties, containing high levels of alloying elements and classified as high-alloy steels. Moreover, for construction applications, fire-resistant steel must also demonstrate good formability, vibration resistance, ductility, and weldability.

3. Mechanical Properties of Fire-resistant Steel at Elevated Temperatures

3.1. Yield Strength

The yield strength of fire-resistant steel at elevated temperatures is a crucial mechanical property. Studies have indicated that at room temperature, the precipitation strengthening of nanoscale TiC precipitates significantly enhances strength. As the titanium content increases from a low level (e.g., from 0.008 wt% to 0.13 wt%), the number of TiC precipitates rises correspondingly, leading to a continuous increase in both yield strength and tensile strength at room temperature. However, this trend changes at 600 °C. When the TiC content is 0.13 wt%, the ratio of yield strength at 600 °C to

that at room temperature (yield strength ratio) drops significantly to about 0.6. For steels with a titanium content of 0.008-0.087 wt%, the yield strength ratio remains above 0.7 and continues to increase with further titanium content increments.[1]

To evaluate the yield strength of high-strength fire-resistant steel produced in China, such as Q460FR, Q420FR, and Q345FR, systematic tensile tests were conducted at high temperatures ranging from 200°C to 800°C, following overfiring and natural cooling. The test results reveal that at 200°C, the yield strength of these fire-resistant steels shows a slight decrease compared to room temperature but still maintains a high load-bearing capacity. For instance, the yield strength of Q460FR steel is reduced by approximately 10% from its room temperature value. As the temperature rises to 400°C, the decline in yield strength becomes more pronounced. The yield strength of Q420FR steel at this point has decreased by about 25% compared to room temperature, indicating the onset of significant softening.

When the temperature further increases to 600°C, the yield strength of Q345FR steel drops to about 50% of its room temperature value. This substantial reduction is due to significant changes in the steel's internal structure, including grain boundary weakening and alterations in second-phase particles. At 800°C, the yield strength of all steel grades drops to a very low level, retaining only 30% to 40% of their room temperature yield strength. Differences in composition and initial microstructure among the steel grades result in variations in yield strength values and trends at specific temperatures.[2]

3.2. Tensile Strength

Tensile strength is a critical mechanical property. By conducting systematic steady-state tensile tests and thermal expansion and deformation tests on domestic Q345FR, Q420FR, and Q460FR fire-resistant steels at high temperatures, the tensile strength within the range of 20-800°C was evaluated. At temperatures below 350-400°C, these steels exhibit higher tensile strength than at room temperature. This is because, within this temperature range, the internal microstructure of the steel undergoes minimal changes, allowing some reinforcing phases to maintain their positive effects, thus preserving the steel's ability to resist external tensile forces. As the temperature gradually increases, this reinforcing effect and structural stability allow the tensile strength to be maintained or even slightly increased.

However, when the temperature exceeds 400°C, the tensile strength begins to decrease rapidly. This is mainly due to the drastic changes in the internal lattice of the steel, such as increased atomic diffusion and easier dislocation movements. The microstructure that originally contributed to strengthening is gradually destroyed, leading to weakening phenomena at the grain boundaries, thereby reducing the steel's ability to withstand tensile loads.[3]

Researchers also conducted experiments on 345MPa grade fire-resistant steel. After heat treatment, the microstructure consisted of a ferrite matrix, a small amount of granular bainite, and M-A islands. As the heat treatment temperature increased, the ferrite grains grew, and the amount of granular bainite and M-A islands decreased, resulting in a decrease in tensile strength, yield strength, and yield-strength ratio, while elongation increased. At a heating temperature of 800°C, the ferrite grains were regular in shape, the bainite distribution was uniform, and the comprehensive mechanical properties were optimal.[4]

For 400MPa grade seismic fire-resistant steel, the tensile strength ranged from 610-650MPa, yield strength from 430-460MPa, total elongation at maximum force from 10.5-12.5%, and yield-to-strength ratio from 1.40-1.44. Even at 600°C, after different holding times, the steel exhibited good strength retention. Similarly, for 500MPa grade steel, the tensile strength ranged from 700-780MPa, yield strength from 520-560MPa, total elongation at maximum force from 9.0-11.0%, and yield-to-

strength ratio from 1.35-1.44, demonstrating good high-temperature strength performance after holding at 600°C for different durations.[5]

3.3. Modulus of Elasticity

The modulus of elasticity measures a material's ability to resist elastic deformation. Changes in the modulus of elasticity of fire-resistant steel at high temperatures directly impact the degree of deformation and load-bearing capacity of steel structures during a fire. Since its modulus of elasticity can maintain a relatively high value at elevated temperatures, steel structures are less likely to lose load-bearing capacity quickly due to excessive deformation. This provides more time for evacuation and fire rescue.

Tests conducted on domestic Q345FR, Q420FR, and Q460FR fire-resistant steels under steady-state tensile conditions and thermal expansion and deformation conditions revealed that the modulus of elasticity remains relatively stable below 350-400°C. Beyond 400°C, the modulus of elasticity starts to decline gradually, but at a slower rate compared to the yield strength and tensile strength. When the temperature is below 450°C, the test values of fire-resistant steel closely match those of ordinary steel as specified in the Technical Code for Fire Protection of Building Steel Structures. [6]Above 450°C, the test values align more closely with the values specified for fire-resistant steel in the code. [3]At 600°C, the modulus of elasticity of fire-resistant steel is about 75% of its room temperature value and remains relatively high until approximately 700°C. Overall, the modulus of elasticity decreases with increasing temperature. In one test involving a plain sleeve connection for fine-grained reinforcement, the modulus of elasticity of fire-resistant steel decreased by 7% at 150°C, 27% at 300°C, 42% at 450°C, and 59% at 600°C compared to room temperature.[7]

3.4. Influence of Alloying Elements on Fire-resistant Steel

Studies have shown that the moderate addition of alloying elements such as Mo, Nb, Ti, and V can enhance the continuous cooling hardening capacity of fire-resistant steel. This promotes the transformation of austenite to bainite, increases the degree of alloying at the microstructural level, refines the grain boundary structure, and consequently improves the material's hardness, toughness, impact resistance, and wear resistance.[8]

In the transformation process of fire-resistant steel, the combined addition of Mo and B inhibits the formation of proeutectoid ferrite and pearlite more effectively than the addition of Mo alone, facilitating the formation of bainite. The hot-rolled test steel exhibits a mixed microstructure of proeutectoid ferrite, granular bainite, and M-A islands, which are crucial for the steel to possess excellent room-temperature and high-temperature properties. Mo primarily influences the properties of fire-resistant steel by affecting its microstructure, while V contributes mainly through precipitation strengthening during later stages.[9]

4. Engineering Applications of Fire-resistant Steel

Research on the application of fire-resistant steel in civil engineering is currently undergoing extensive study and promotion in China. Compared with foreign countries, China's research started later, but fire-resistant steel materials still hold significant potential for application. The progress of global research on fire-resistant steel is mainly reflected in the following aspects:

4.1. High-rise and super-high-rise buildings

In high-rise and ultra-high-rise buildings, structural stability and fire resistance are crucial. These buildings primarily utilize frame structures, frame-core structures, and similar designs. For instance,

the Shanghai Centre Building employs a giant frame-core-core-extension truss system to withstand lateral forces.[10] Consequently, fire-resistant steel is frequently used in the construction of load-bearing components such as columns and beams, as well as in floor slabs, staircases, and fire doors. This steel maintains its high strength during a fire, preventing rapid softening, deformation, or collapse due to high temperatures, thereby providing valuable time for evacuation and fire rescue. Additionally, the high durability and reliability of fire-resistant steel can reduce the costs associated with staircase maintenance and replacement, extend the building's service life, and save on overall expenses.

4.2. Large-span Buildings

Fire-resistant steel is suitable for large-span building structures such as gymnasiums, exhibition halls, and airport terminals, meeting both strength and fire resistance requirements. Its high strength minimizes the size and weight of structural components while maintaining stability during a fire, thereby ensuring the safety of large spaces.

4.3. Fire Compartment Materials

Fire-resistant steel demonstrates numerous advantages and significant value when used in fire compartment materials. From the perspective of structural stability, fire compartments impose stringent fire resistance requirements on fireproof partition walls and other structures, typically requiring a fire resistance rating of no less than 3.00 hours. This ensures that in the event of a fire, the entire structure will not easily collapse, effectively and efficiently isolating the fire source within a certain range. This containment prevents the uncontrolled spread of fire, providing valuable time for occupants to evacuate and creating favorable conditions for firefighting efforts.

Regarding fire performance, the chemical composition of fire-resistant steel is carefully engineered, and its microstructure possesses special characteristics. These factors collectively enable the steel to exhibit excellent resistance to combustion and deformation in high-temperature environments. Consequently, this fundamentally enhances the overall fire resistance of fire compartments, allowing them to better withstand damage caused by fires and minimizing the impact on surrounding areas.

4.4. Bridge Works

Fire-resistant steel enhances the structural load-bearing capacity of bridges due to its high yield strength, tensile strength, and elongation. It can withstand complex stresses in bridge structures and is used in main girders, cross girders, piers, columns, and other critical stress points. This improves the bearing capacity of the bridge, enabling it to accommodate larger loads and meet the demands of large-span bridge construction.

Additionally, fire-resistant steel extends the service life of bridges with its excellent corrosion resistance and durability. It can resist external environmental factors, reducing structural damage caused by corrosion and other issues. Consequently, this extends the service life of reinforced concrete bridges, lowering the frequency and cost of repairs and reinforcements.

Moreover, fire-resistant steel is easy to construct and connect. It has good weldability, cold bending performance, cutability, and connectivity, facilitating processing and installation during bridge construction. It can be connected with ordinary steel bars through welding and tying to form an integrated steel framework, ensuring the strength and fire-resistant performance of the connection

5. Conclusion

In summary, the application of fire-resistant steel in civil engineering is of great significance. An in-depth discussion of its performance characteristics, current research progress, and practical applications in various civil engineering structures highlights the substantial benefits of fire-resistant steel in enhancing building fire safety and ensuring structural stability. However, challenges such as cost control, performance optimization, and continuous improvement of relevant standards and codes remain. Future efforts should focus on strengthening interdisciplinary cooperation, investing more in scientific research on fire-resistant steel, and expanding its application in civil engineering to create safer, more reliable buildings. This will contribute to the industry's advancement towards a safer and more sustainable development.

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