Review

A Summary of the Application of High-strength Steel in Bridge Engineering

Fangjian Hu

Shanghai Urban Construction Design & Research Institute (Group) Co., Ltd, Shanghai 200125, China;
Correspondence: hufangjian@sucdri.com

Abstract: Regarding the application of high-strength steel in bridges, this paper describes the development and changes in the properties of high-strength steel through a review of the relevant literature from the past five years. This paper introduces the research status of high-strength steel, steel strands and high-strength rebars and focuses on the research status and application level of HRB500 and HRB600 high-strength rebars, combined with their performance characteristics and application cases, and prospects for corresponding development and application in the future.

Keywords: high-strength steel; high-strength steel bar; high-strength weathering steel

1 Introduction

The creation of innovative materials is an important driving force for the development of bridge structures. Wood, stone and other natural materials were the main structural materials of ancient bridges. With the rise of the Industrial Revolution and the impact of the Second World War, steel and concrete have gradually replaced natural materials as the main structural materials of bridge engineering and have been used in bridge engineering for hundreds of years [1]. In addition to traditional concrete and steel, with the continuous development of materials science in recent years, the emergence of high-performance materials provides new opportunities for the future development of bridge engineering. This paper summarizes the application level, performance characteristics and application cases of high-strength steel in bridge engineering at home and abroad by referring to the relevant literature from the past five years.

With the development of China's steel industry and the continuous optimization of steel production technology, more new types of steel with high strength and superior performance have appeared. Welding metal materials and welding technology with sufficient strength, good ductility and toughness are also being gradually improved, which has made the promotion and use of high-strength steel gradually possible. At present, a large number of new materials, new structures and new processes, such as the application of new Q500q steel materials, the application of all-welded joints and the overall steel deck, the design of kilometer railway cable-stayed bridges and suspension bridges, and the application of new Q500q steel deck materials, have emerged in the design field of railway steel bridges in China.

In recent years, high-strength steel structures have been successfully applied in many buildings and bridge structures at home and abroad because of their significant advantages in terms of structural bearing performance, building functions and social and economic benefits. Compared with that of ordinary structural steel, the use of high-strength steel in bridge engineering has obvious advantages. (1) The yield performance of high-strength steel more easily meets the design needs, reduces the size of members and structural weight, and increases the net usable space. (2) The construction period of steel structure bridges is short, and the durability is strong. (3) Digesting a part of steel production capacity can create considerable economic

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benefits in the long run, reduce construction costs to a certain extent, and is conducive to domestic promotion. ④ Steel bridge construction produces less waste, and the steel used is green and environmentally friendly, which is in line with the concept of construction economization.

However, the mechanical properties, fracture toughness and fatigue properties of high-strength steel are changed due to the great differences between high-strength steel and ordinary steel in the smelting and rolling process, crystal structure, chemical composition and post-treatment technology. An improve in strength increases the yield ratio of the steel, which also increases the sensitivity of the steel to temperature and defects. Therefore, high-strength steel structure members are more prone to brittle fracture. Brittle fracture failure often occurs suddenly, the stress level of the steel member is very low, and there is no obvious plastic deformation. Many factors affect the brittle fracture of steel structure members, including the ambient temperature, stress concentration, strain state, material properties, and welding process. Most high-strength steel structures are large welded structures, so cracks and even fractures often occur at the welded joints, and the fatigue damage of welded steel structures mainly occurs at the welded joints. The brittle fracture and fatigue of steel structures are closely related to their safety reliability and fatigue service life. Factors that affect the fatigue performance of welded steel structure members generally include section size, stress concentration at the gap, welding defects, welding process, welding residual stress, material properties, loading conditions, and engineering environmental conditions, etc.

In recent years, high-strength steel has been widely used in various practical projects at home and abroad and has gradually been applied in construction engineering and bridge engineering in China..

2 Development History of High-strength Steel at Home and Abroad

High-strength steel was first used in machinery, pressure vessels and pipelines, nuclear reactor shells, aviation, ships and other fields of engineering, and the application of bridge engineering and construction engineering started late. Since the 1960s, high-strength steel structures were first applied in the engineering industry in Japan and then gradually expanded to other countries, such as the United States, Europe, and Australia. High-strength steel structure engineering mainly involves bridge engineering and construction engineering, such as long-span roof space structures, high-rise ultrahigh floor building bottom column structures, long-span bridge structures, and offshore platform structures.

In recent decades, with the development of metal smelting and rolling technology, great progress has been made in the research and production of high-strength steel for bridges at home and abroad. High-strength steel bridge steel has a high yield strength but also has outstanding advantages in terms of fracture toughness, weldability, corrosion resistance and so on. At present, many countries have developed multiple series of high-strength steel products for bridges according to their national conditions, such as HPS485W, HPSS690W in the United States, BHS500, BHS700 in Japan, S460M / 690M in Europe, and Q420, Q460, Q500 in China. The strength of the bridge steel is above 420 MPa.

The United States has carried out much research and development on high-performance steel (HPS) for bridges, and after years of effort, the United States has developed a series of high-performance steel: HPS50W, HPS70W and HPS100W[2]. High-performance steel has better tensile strength, toughness, weldability, cold working performance and corrosion resistance than common low-carbon steel, which is highly important for promoting the development of bridges of long spans and saving types. In terms of chemical composition, HPS steel has a lower carbon content than traditional steel, and other elements compensate for the strength loss caused by the lower carbon content. In terms of weldability, HPS steel is easy to weld with ordinary steel, allowing a high input temperature during welding, usually without preheating or welding at a low preheating temperature. In terms of fracture toughness, HPSs have higher toughness and lower tough-brittle transition temperatures, which means that high-performance steels can be used in bridge structures in colder regions. In terms of weather resistance, a new type of weathering steel has been developed by adding alloying elements such as nickel and copper. This new type of steel has better corrosion resistance than traditional steel and does not require coating or other anti-corrosion technologies.

Japan's research on bridge high-strength steel has focused on improving the strength, weldability, toughness, fatigue and weather resistance of bridge steel; popularizing the application of bridge high-strength steel in large steel bridges; and achieving remarkable economic and social benefits. To reduce the total cost during the life cycle of steel bridges, Japan has developed high-strength steel for bridges (BHS500W or BHS700W); BHS500 is suitable for small-span and medium-span bridges, and BHS700 is suitable for long-span bridges [3]. BHS steel not only has high yield strength and tensile strength but also has good fracture toughness, weldability, manufacturability, formability and weather resistance. At the same time, Japan has developed new welding technologies, such as the low transition temperature welding method, to improve the fatigue properties of steel and has built a number of high-performance steel bridges using BHS steel. As of April 2003, a total of 19400 tons of new nickel-bearing steel, including test steel, had been used in Japanese bridges since 1997. According to 1999 statistics, Japan's high-performance steel accounts for 22% of all bridge steel, of which corrosion-resistant steel accounts for nearly 70% of high-performance steel (accounting for 15% of all steel production).

Europe has carried out a systematic study on the fatigue fracture performance and structural stability of high-strength steel used in bridges and is committed to establishing the design criteria of high-strength steel bridges and incorporating them into the latest European code system. According to the European standard, the maximum content of alloy elements in high-strength steel is very conservative, the alloy content is affected by the grade of steel, and the chemical composition of steel also varies with the thickness. Compared with the commonly used European construction steel S355J2, the strength requirements of S460ML, S460QL and S690QL vary with the thickness of the steel plate. High-strength steels with yield strengths between 335 MPa and 690 MPa are suitable for steel structure bridges, and their manufacturing properties are similar to those of ordinary steel. The addition of alloying elements to hot-rolled steel has not been emphasized, but the toughness is high, and the weldability is good. Under the premise of ensuring toughness and weldability, quenched and tempered steel can fully exert the advantages of high strength, which improves the designer's design room and reduces the impact on the environment.

In recent years, China's bridge engineering and steel industry have made remarkable achievements in the development of high-strength bridge steel and research on high-strength steel structure bridges. In the long run, the steel used for highway steel bridges in China are mainly low-alloy high-strength structural steel with a yield strength of 345 MPa, and structural steel with a higher strength level is rarely applied. In 1993, the Jiujiang Yangtze River Bridge on the Beijing—Jiujiang Line used 420 MPa 15MnVNq steel, but it has not been widely used due to poor weldability. At the same time as the rapid development of high-strength steel and high-strength steel bridges in foreign countries, domestic large steel enterprises have successively developed high-performance and high-strength steel for domestic bridges, such as the A709M-HPS 485W high-performance steel plate developed by the HBIS (Hebei Iron and Steel Group) Wustell Co., which was successfully applied to the new San Francisco Bay Bridge in the United States. Anshan Iron & Steel Corp has developed a new generation of high-performance bridge steel series, Q345qE (NH), Q370qE (NH), Q420qE (NH), Q500qE (NH), and Q690qE (NH), using the ultralow carbon bainite steel process route. Wuhan Iron and Steel Company has developed a series of ultralow carbon bainite weather-resistant bridge steels, including

WNQ490, WNQ570, WNQ590, WNQ690 and other strength grades. [4] According to the national standards for " High strength low alloy structural steels" (GB/T 1591—2008), " Structural steel for bridge" (GB/T 714—2008) and the actual product performance, Q345~Q420 structural steel has reached a very high level in toughness, weldability, cold working and other aspects, basically equivalent to similar international advanced products. However, compared with those in the United States, Europe, Japan and other countries, the yield strength of steel with a bridge strength greater than 500 MPa is slightly lower.

3 Research Status of High-strength Steel and Steel Wire

3.1 High-strength Steel

High-strength steel bridges have the advantages of a strong span ability, short construction period, high degree of industrialization, low carbon availability and environmental friendliness. To ensure the safe construction of high-strength steel bridges in our country and provide a reference and guidance for further research on highway high-strength steel bridges in our country, this paper summarizes the main research results of domestic and foreign scholars on high-strength steel, including the residual stress of high-strength steel, the stability of high-strength steel components and the fatigue properties of high-strength steel components.

The residual stress has a great influence on the bearing capacity and stability of steel members. In recent years, scholars at home and abroad have carried out experimental research and theoretical analysis on the residual stress of high-strength steel. The research results [5, 6] show that the magnitude and distribution of the residual stress of high-strength steel and general steel are not very different. For high-strength steel, the ratio of residual stress to yield strength is smaller than that of ordinary steel, and this ratio has a great impact on the bearing capacity of the member rather than the absolute value of the residual stress, so the impact of residual stress on high-strength steel is less than that on ordinary steel. According to the existing test results, the residual compressive stress distribution of high-strength steel is related to the width/thickness ratio of the plate. For the welded section, the value of the residual tensile stress is often close to the yield strength of the steel, and due to the self-equilibrium characteristics of the residual stress, the magnitude of the residual compressive stress is related to the width/thickness ratio of the member plate [7].

Domestic and foreign scholars have performed much research on the stability of welded high-strength steel components. For the overall stability of welded high-strength steel structures, several researchers proposed the expression of the overall stability factor by fitting [8] and compared the test results with the design criteria in the current design codes of various countries. In addition, the existing research results also show that the overall stability factor of high-strength steel columns is greater than that of ordinary steel columns when the overall stability ultimate bearing capacity is reached. Therefore, when designing high-strength steel members, a ratio higher than the existing ratio can be used. Specification for a greater overall stability factor [9]. This is mainly because the impact of initial defects (geometrical initial defects and residual stress, etc.) on components of high-strength steel columns is much smaller than that of ordinary steel columns [10]. Domestic and foreign scholars have conducted a large number of experiments and numerical analyses on the local stability of welded high-strength steel members [11], and the restrictions on the width-to-thickness ratio of the flange of the axial compression column in the domestic “Code for design of steel structures” (GB50017—2003) are still applicable to high-strength steel columns. However, the section size of existing test components is small, and further research on large test components is needed to obtain more comprehensive results.

There are many studies on the fatigue properties of high-strength steel in foreign countries, and the related research has focused on the influence of crack propagation, steel strength grade, steel plate thickness, welding technology, post-welding treatment methods and other factors on fatigue. Shi et al. [12] conducted a test on the fatigue properties of high-strength structural steel Q460D, focusing on the S-N curve of the Q460D base metal, and the test results showed that the fatigue strength of Q460D steel at 2 million cycles was greater than that calculated according to the "Code for design of steel structures" (GB50017—2003). Cheng et al. [13] carried out corresponding fatigue test studies on Q420B and Q420C steels and obtained the fatigue life of the two steels under different stress levels. The test results show that the fatigue properties of the Q420C steel are greater than those of the Q420B steel under the same conditions. By comparing the test results with the calculated values of the "Code for design of steel structures" (GB50017—2003), it is found that the test results are much greater than the calculated values of the norm. Zong et al. tested the fatigue crack growth rate and fatigue crack growth threshold of WNQ570 bridge steel and its butt weld and obtained fatigue crack growth parameters with a 95% guarantee rate by using two different data fitting methods. The results show that the WNQ570 base metal and butt weld have good anti-fatigue crack propagation properties, and the fatigue crack propagation rate of the butt weld is greater than that of the WNQ570 base metal.

3.2 High-strength Steel Wire

In some long-span bridges, such as cable-stayed bridges and suspension bridges, the slings and stay cables are usually made of high-strength steel wire. However, under the action of the external environment and repeated vehicle loads, the sling is in a state of high stress for a long time, and fatigue cracking is a kind of load-induced fatigue cracking. At present, many researchers have studied the mechanical behavior and fatigue properties of high-strength steel wires. SC Barton et al. [14] studied the tensile properties of corroded steel wires under salt spray, drying and high-temperature conditions at 100% relative humidity and reported that the elongation of steel wires was greatly affected by corrosion. S. Nakamura et al. [15] compared the mechanical properties of scratched steel wire with those of corroded steel wire. The shape of the notch is considered to be the main factor for reducing the fatigue strength of steel wires. Li et al. [16] conducted a fatigue performance test on corroded high-strength steel wire used for arch bridge sling. The fatigue property of steel wires is sensitive to the degree of corrosion initially and then becoming insensitive later. Qiao et al. [17] conducted static tensile, fatigue and torsion tests on steel wires and obtained the SN curve of steel wires. Ma et al. [18] tested the fatigue crack growth performance of galvanized high-strength steel wires commonly used in bridges. The effect of the stress ratio and stress amplitude on the fatigue crack propagation performance of steel wires was studied, and the relationship between the crack propagation depth and the number of fatigue cycles under different stress ratios was obtained. The N curve is fitted to the fatigue crack growth rate model of high-strength steel wires. Huang et al. [19] conducted an in-depth study on the fatigue performance, corrosion resistance, and vibration control scheme of high-strength cables using OVM250 cable as the subject. The results have been successfully applied in multiple cable-stayed bridge projects.

4 Research Status of HRB500 and HRB600 High-strength Rebars

4.1 Research on the Properties of HRB500 High-strength Rebars

An HRB500 high-strength steel bar is a micro-alloy hot-rolled ribbed rebar with a tensile yield strength of 500 MPa. It has the characteristics of high strength, good ductility, stable mechanical properties and good construction adaptability. Replacing HRB335 ordinary steel bars with HR500 high-strength steel bars can not only increase the structural safety reserve and reduce the project cost but also reduce material consumption and promote energy savings and emission reductions. In 2010, China revised the "Code for the design of Concrete Structures" (GB 50010—2002) and issued a new "Code for the design of Concrete Structures" (GB 50010—2010), which officially included HRB500 high-strength steel bars in the new code.

At present, there are more than 70 iron and steel enterprises qualified to produce HRB500 high-strength steel bars in the country. These enterprises are distributed in 24 provinces, municipalities and autonomous regions, of which Hebei, Shandong, Jiangsu and Anhui account for more than half of the national total. Rebar products cover various sizes from 6 to 50 mm. The production process is mainly microalloying, but post-rolling heat treatment and ultrafine crystallization are also used. The technical level of production enterprises, represented by HBIS Chengsteel Co. and HBIS Tangsteel Co., has reached the international advanced level.

4.1.1 Research on the Flexural Performance of HRB500 RC (Reinforced Concrete) Beams

Sun et al. [20] conducted flexural performance tests on 3 reinforced light aggregate concrete composite beams with HRB500 combination sealing stirrup and longitudinal reinforcement and 3 contrast specimens under different reinforcement ratios. The results showed that the failure forms and bending properties of the reinforced lightweight aggregate concrete composite beams with HRB500 combined with closed stirrup and longitudinal reinforcement were similar to those of the whole cast contrast beams. The assumption of the normal section of the beams is still applicable, and the bending capacity, cracking load and deflection of the normal section can still be calculated according to the calculation formulas in the current code ”Technical specification for lightweight aggregate concrete structures” (JGJ 12—2006).

4.1.2 Research on the Compressive Performance of HRB500 RC Columns

Zhang [21] conducted experimental research on 8 axial compression members of light aggregate concrete and obtained test results of the mechanical properties and failure forms of the axial compression members of light aggregate concrete equipped with HRB500 rebar, as well as the load–strain relationship curve. The co-working performance of HRB500 steel bars and lightweight aggregate concrete is analyzed, and a design calculation method for axial compression members is proposed. The results show that increasing the strength, reinforcement ratio and stirrup ratio of light orthopedic concrete can improve the peak compressive strain and ultimate bearing capacity of light aggregate concrete members. HRB500 steel bars have good working performance in light aggregate concrete axial compression members, and their strength can be fully utilized. Xiao Zhimin [22, 23] et al. believe that the HRB500 steel reinforcement framework is beneficial for improving the local compression capacity of specimens, but its effect is very small.

4.1.3 Research on the Shear Performance of HRB500 RC Beams

Bian [24] analyzed the effects of the concrete strength grade, steel fiber content and stirrup configuration on the shear bearing capacity of beams through shear tests of steel fiber-reinforced concrete beams with high strength and high performance. The results showed that both an increase in the concrete strength and the addition of steel fibers could significantly improve the shear bearing capacity of the beams and allow the stirrup to play a full role. Based on the shear test data of nonventral reinforced concrete beams and beams with ventral reinforced beams at home and abroad, an empirical formula for calculating the shear capacity of steel fiber high-strength reinforced concrete beams with ventral reinforcement is proposed and verified. The calculated results are in good agreement with the measured values.

4.1.4 Research on the Seismic Performance of HRB500 RC Members

To analyze the seismic performance of high-strength concrete columns with large-spacing high-strength longitudinal ribs, Tang et al. [25] conducted low-cycle reciprocating loading tests on four C80 high-strength concrete columns with large-spacing HRB500 high-strength longitudinal ribs. The test pieces were divided according to whether the intermediate structural longitudinal reinforcement and tension reinforcement are set, whether the reinforcement ratio of the stirrup is increased, and whether the conventional reinforcement is compared. The results show that the hysteretic curve of the C80 high-strength concrete column with large-spacing

HRB500 high-strength longitudinal reinforcement is relatively full, the yield load and peak load are similar to those of ordinary reinforcement specimens, and the descending section of the skeleton curve can maintain stability. To ensure good ductility, the structural longitudinal bar and the middle tension bar should be set up. The bearing capacity can be designed and calculated according to the method specified in the current code, and there is a certain strength reserve. The hysteresis curves of the specimens with a higher reinforcement ratio of the stirrup became fuller.

4.2 Research on the Properties of HRB600 High-strength Rebars

HRB600 grade high-strength rebar has been included in the national standard "Steel for the reinforcement of concrete—Part 2: Hot-rolled ribbed bars" (GB/T 1499.2—2018). The design method of HRB600 steel bars is not specified in the current "Code for the design of Concrete Structures" (GB 50010—2010) in China. The efficient use of HRB600 grade steel bars in concrete structure engineering to provide a reasonable structural design method has become an urgent problem in the construction industry. Several research institutions have carried out relevant research.

4.2.1 Research on the Flexural Performance of HRB600 RC Beams

Wang [26], Xiong [27], Zhang [28-31] and Cui [32] have carried out experimental studies on the flexural performance of bonded, unbonded and partially bonded reinforced concrete beams and prestressed reinforced concrete beams equipped with HRB600 steel bars. Those authors analyzed whether the calculation formulas for the flexural bearing capacity and deflection in the "Code for the design of Concrete Structures" (GB 50010—2010) are suitable for HRB600 rebar. The results show that the bending performance of the concrete beam with HRB600 reinforcement is the same as that of the ordinary reinforced concrete beam, and the bearing capacity and deflection can be calculated according to the calculation formula in the current code. According to Wang [26], the overall flexural performance (crack distribution, failure pattern and ductility) of HRB600 grade reinforced concrete beams is basically the same as that of ordinary reinforced concrete beams. According to the combination of quasi-permanent values and considering the influence of long-term loads, the deflection of the members meets the limit requirements of the "Code for the design of Concrete Structures" (GB 50010—2010). However, the crack width of the component corresponding to the above load value does not meet the limit requirements stipulated in the GB 50010—2010 code. Xiong [27] studied the bending mechanical properties of concrete beams equipped with 12 HTRB600 rebars and 8 HRB600 rebars through bending tests. According to the test results, the bending capacity of concrete beams equipped with 600 MPa rebar can still be analyzed on the basis of the assumption of a flat section. Zhang [28-31] showed that the strain change in steel fiber-reinforced concrete beams equipped with 600 MPa high-strength reinforcement is consistent with the assumption of a flat section. Steel fibers can effectively improve the bending cracking load and deformation capacity of high-strength concrete beams and inhibit the generation and development of cracks. Moreover, with the increase of steel fiber content, the bending capacity of steel fiber high-strength concrete beams also increases. The current code "Technical specification for fiber reinforced concrete structures" (CECS 38: 2004) still has good applicability for calculating the ultimate bearing force, maximum crack width and deflection of HRB600 grade reinforced steel fiber high-strength concrete beams.

4.2.2 Research on the Compressive Performance of HRB600 RC Columns

Zhang et al. [33] theoretically calculated the height of the limit relative to the compression zone ξ_b by studying the symmetric reinforcement of eccentric compression columns of concrete equipped with HRB600-grade rebar. Because the design values of the tensile and compressive strengths of HRB600-grade rebar are not equal, based on the existing "Code for the design of Concrete Structures" (GB 50010—2010), the basic formula of eccentric compression of symmetrical reinforcement size and the discriminant formula of eccentric compression type are derived, and the corresponding calculation method of section design is given. Zhang et al. [34, 35] reported that with the increase of concrete strength grade, the bearing capacity of HRB600-strengthened high-strength concrete columns increased significantly, the axial compression stiffness increased, and the decreasing section of the load–deformation curve became steeper. With increasing stirrup ratio, the bearing capacity and ductility of the column improved, and the axial compression stiffness slightly increased. With increasing stirrup strength, the load bearing force and axial compression stiffness of the column change little, but the performance of the column after the peak obviously improved. When the compressive strength of the HRB600 steel bar is 500 MPa, there is a sufficient safety reserve according to the bearing capacity calculation formula recommended by China, the United States and Japan in the Code for Design of Concrete Structures.

4.2.3 Research on the Shear Performance of HRB600 RC Beams

Zhang et al. [36, 37] showed that as the reinforcement ratio of longitudinal reinforcement increases, the cracking load and ultimate load of the inclined section of HRB600-strengthened high-strength concrete beams increase, and the width of inclined cracks decreases. Steel fibers can effectively increase the cracking load of high-strength concrete beams and limit the generation and development of inclined cracks. With increasing steel fiber content, the shear capacity of high-strength concrete beams increases. The design and calculation of the shear capacity of high-strength concrete beams and high-strength steel fiber concrete beams with HRB600 longitudinal reinforcement are safe.

4.2.4 Research on the Seismic Performance of HRB600 RC Members

Rong et al. [38] conducted low-cycle reciprocating load tests on 6 concrete rectangular columns reinforced with HRB600E with different coaxial compression ratios, reinforcement strengths and longitudinal reinforcement ratios and obtained hysteretic curves, skeleton curves and longitudinal reinforcement strain curves of the specimens. The results show that the failure characteristics of the HRB600E reinforced concrete column are similar to those of the ordinary reinforced concrete column. The hysteretic characteristics of HRB600E high-strength reinforcement specimens can be improved by reducing the axial compression ratio or increasing the strength of the reinforcement. When high-strength steel bars and high-strength concrete are used together, the mechanical performance of the member is better. Zhang et al. [39] reported that steel fiber high-strength concrete columns equipped with HRB600 rebar exhibited good deformation ability. With increasing steel fiber content, the displacement ductility coefficient of the high-strength concrete columns gradually increased. Based on the test data, the restoring force model of the HRB600 reinforced steel fiber high-strength concrete column has good calculation accuracy. This type of column can meet the requirements of the current seismic design code and is suitable for popularization and application. Zhang et al. [40] believe that the matching effect between HRB600 grade steel bars and C80 concrete is better. A reasonable stirrup configuration can increase the ductility coefficient of HRB600-strengthened high-strength concrete columns to greater than 4.0 under the condition of a high axial compression ratio.

5 Application of High-strength Steel in Bridge Engineering

5.1 Application Status in Foreign Countries

In developed countries worldwide, the most widely used field of high-strength steel is bridge engineering, which has achieved good results. As early as the 1950s and 1960s, the United States and Japan launched high-strength steel with a yield strength of 500~800 MPa and used it in bridge construction. However, because high-strength steel cannot fully meet the requirements of modern bridges in terms of material toughness and weldability, its popularization in modern bridge engineering is limited to a certain extent.

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The U.S. Transportation Department used the Snyder Bridge built in 1997 to test the performance of HPS70W high-strength steel with a yield strength of 485 MPa and replaced all the HPSSOW steel in the original design scheme with HPS70W steel. This overly conservative design paves the way for the promotion and application of HPS70W high-strength steel. After the Snyder Bridge, HPS70W high-strength steel began to be widely used in bridge structures in the United States. The Martin Creek Bridge in Tennessee, Ford City Bridge in Pennsylvania, Berkshire over, Muitzes Kill Bridge and I-90Exit54 Bridge in New York State all use HPS70W high-strength steel to a greater or lesser extent. Good economic benefits have been achieved [41].

The Riviere Henri Bridge in Quebec City, Canada, was the first bridge in Canada to use high-strength steel. The main beam is 2.01 meters high, and HPS485 W high-strength steel is used. The bridge is mainly used to evaluate the material properties of HPS485W high-strength steel and its feasibility for bridge structures [41]. The Verr and Viaduct in Italy, completed in 2002, is part of the Mont Blanc-Aosta motorway. The bridge uses orthogonality bridge panels, high-strength steel pipe sections for the top deduced beams, and high-strength steel S690, and the span of the sub-beams can reach 85 m. It crosses the Narrow Valley and the Dora Baltea River. [42]

In 1974, Japan used 1,073 tons of 700 MPa grade steel and 4,195 tons of 800 MPa grade high-strength steel in the construction of the Minato Ohashi Bridge, accounting for 13% of the total steel used. Japan's Akashi Kaikyo Bridge was the world's largest suspension bridge when it was built, and a large amount of high-strength steel was used, some of which even have a strength of up to 1770 MPa.

The Mittadalen hybrid beam bridge in Sweden uses S690 high-strength steel for the lower flange, and the 48-meter-span military bridge uses S960 and S1100 high-strength steel, which greatly saves material and reduces self-weight.

The Millau Viaduct Bridge in France and the Rhine Bridge Dusseldorf-ILverish bridge in Germany both use S460 high-strength steel. To reduce the pier size and meet the appearance requirements of the Nesenbachtalbruke bridge in Germany, 5690 high-strength steel is used for the compression members. The Dusseldorf-Ilverich Cable-stayed Bridge in Germany is located near the A44 motorway in Dusseldorf, close to Dusseldorf Airport. Due to the limited height of the bridge, S460ML high-strength steel was used, and the economic effect was remarkable [41]. The coastal bridge, located in Tokyo Bay, Japan, is a truss bridge with a total length of 760 m and an intermediate span of 440 m. The height of the middle span of the bridge should meet the requirements of the shipping traffic under the bridge, and the total height of the bridge should not be too high due to the operation of the nearby Haneda airport. Such harsh conditions cause some of the struts in the trusses at the middle span piers to bear considerable tension, so more than 20,000 tons of BHS500 and BHS700 high-strength steel were used in the bridge, which met the design needs [41].

In general, the current high-strength steel has not yet been widely used in engineering, and the testing or design requirements of steel are generally harsh. According to existing engineering examples, high-strength steel has good promotion value in China: not only can theoretically make the steel plate design thinner, reduce the structural weight, but also reduce the welding size and shorten the construction period. With the advancement of welding technology, the service life of steel bridges will also be further extended.

5.2 Application Status in China

At present, China's steel production capacity is seriously excess, and promoting the construction of steel structure bridges is in line with the national industrial policy of stimulating domestic demand. Compared with concrete, steel can be reused in line with the goals of national energy-saving emission reduction and green environmental protection construction. The No. 115 document "Guiding Opinions on Promoting the Construction of Highway Steel Structure Bridges" issued by the Ministry of Communications in 2016 clearly noted that by the end of the "13th Five-Year Plan", new large bridges and ultralong span bridges should be constructed with steel structures as the main body, and newly rebuilt bridges should be constructed with steel structures. The proportion of steel structures in other bridges has increased significantly.

The good weldability of bridge steel is considered to be an important index for its popularization and application. In the development process of China's bridge steel, steel with poor weldability (such as 15MnVNq steel) has been eliminated, and steel with good weldability (such as 14MnNbq steel) has been widely used. The connection mode of bridge members has gradually developed from riveting and bolt welding to full welding.

In recent years, in the development of bridge steel in China, due to the demand for high-strength and good weldability steel in the bridge engineering community, prototypes of domestic high-performance steel, such as Q420qE (WNQ570) steel, have been developed. The Jiujiang Yangtze River Bridge built in 1992 used 15MnVNq steel (yield strength ≥420 MPa when plate thickness ≤16 mm) produced by the Anshan I&S Co. The 15MnVNq steel is similar to high-strength steel used abroad. However, due to the method of adding vanadium to the steel to increase its strength, the steel plate exhibits poor low-temperature toughness and welding performance. It is highly sensitive to welding cold and hot cracks, hence it is rarely used in future bridge construction [43].

The Wuhu Yangtze River Bridge, opened to traffic in September 2000, uses 14MnNbq (Q370) steel produced by Wuhan Iron and Steel (Group) Company. New steel welding technology has been widely recognized by domestic bridge designers. The Beijing-Shanghai high-speed railway Nanjing Dashengguan Yangtze River Bridge uses Q420qE bridge steel produced by Wuhan Iron and Steel (Group) Company for the first time. The steel adopts TMCP+ tempering process, which is similar to that of foreign high-performance steel and has a high yield strength. The carbon equivalent increase is not large, and the welding performance is good. The Nanjing Dashengguan Bridge adopts three kinds of steel, Q345qD, Q370qE and Q420q, with a mixed design, of which Q420qE is used for pressure members with a force of more than 600 tons; this is the first time that this steel grade has been applied to railway bridge construction.

5.3 Application of High-strength Weathering Steel

High-strength weathering steel is a type of high-performance and high-strength steel. It combines excellent corrosion resistance with mechanical properties, making it an excellent choice for structural steel applications. Compared with high-strength structural steel, high-strength weathering steel has greater corrosion resistance in ordinary atmospheric environments. Compared with ordinary carbon steel or ordinary weathering steel, high-strength weathering steel can greatly reduce the amount of steel. In use, if a painting-free design is adopted, it can improve the construction speed, shorten the construction period, benefit environmental protection and reduce the whole life cycle cost [44].

In the United States, Bridges on the New Jersey Turnpike, built in 1964, were the first to utilize weathering steel and adopted a paint-free design. In 1977, the world's largest span arch Bridge, the New River Gorge Bridge, was completed using Cor-ten steel. In 2000, the Ford City Bridge was completed and opened to traffic using a mixture of HPS 70 W and Grade 50 W steel, which saved 20% of the steel used. In 1989, the United States Federal Highway Administration (FHWA) developed guidelines for the design of weathering steel structures without painting. By 1993, the United States had reached more than 23,000 noncoated weathering steel bridges. At present, weathering steel bridges in the United States account for approximately 50% of all steel bridges. With the slowdown of infrastructure construction in the United States, the construction speed of weathering steel bridges in the United States is also limited.

In 1969, Japan built its first weathering steel bridge. The Ōtonegawa Bridge on the Shihoro Line, completed in 1981, and the Aganogawa-Omae Bridge on the Ban'etsu West Line, completed in 1983, both utilized weathering steel. To better utilize weathering steel bridges, the "Guidelines for the Design and Construction of

Paint-Free Weathering Steel Bridges" were formulated in 1985. In 1997-1998, the standard for the use of weather-resistant steel considering deicing salt was formulated. At present, approximately 20% of the bridges in Japan use weathering steel, of which 70% use a paint-free design and 20% use rust layer stabilization treatment technology.

In Europe, Germany began constructing weathering steel bridges in 1969, while the United Kingdom started in 1970. In Canada, 90% of newly built steel bridges utilize weathering steel. South Korea began constructing weathering steel bridges in 1992, and to date, there are over 20 such bridges.

In China, the Beijing-Guangzhou Railway Xunsi River Bridge built in 1991 used weathering steel, of which two spans were painted, one span was paint-free, and later all were painted. The Houdingxiang Bridge, which was completed in 2013, is a real paint-free weathering steel bridge. With the development of China's weathering steel, in 2013, the China Railway built the Alaska Tanana River Railway Bridge in the United States, which is a paint-free bridge with a total weight of approximately 6,700 tons. The Puwan 16th cross-sea Bridge, which started construction in April 2016, uses weathering steel. In May 2016, weathering steel was used for the construction of the Tangmu Yarlung Zangbo River Bridge, in which the bridge floor was painted free and covered with an arch rib coating; this bridge is also the largest span of railway concrete-filled steel tube arch bridges in China.

5.4 Engineering Applications of HRB500 and HRB600

In the “Specifications for Seismic Design of Highway Bridges” (JTG/T 2231-01 2020), to improve resource utilization and promote the use of high-strength and high-performance materials, the strength grades of steel bars used in concrete bridge and culvert projects are adjusted. The HPB235 and HRB335 steel bars were removed, and the HRBF400, HRB500, and HRBF500 steel bar construction technology requirements were increased, which is consistent with the design specifications.

During the construction of the Hong Kong-Zhuhai-Macao Bridge, the main types of steel bars used were HRB400E and HRB500E. In the critical sections of the towers of the Pingtang Extra-large Bridge in Guizhou, HRB500E high-strength seismic reinforcement bars were utilized, with a total of over 5,000 tons of HRB500E high-strength seismic reinforcement bars in specifications ranging from Φ36mm to Φ40mm.

The concrete bridges and prestressed concrete bridges of the Qugang Expressway originally designed with HRB400 ordinary steel bars as the main load-bearing bars were later modified to adopt HRB500 high-strength steel bars [45]. During the design modification, three schemes were compared:

Scheme 1: The outermost load-bearing steel bars of the bottom slab were replaced from the original HRB400 to HRB500 high-strength steel bars. To conserve materials and reduce the diameter of the steel bars, the diameter of the outermost load-bearing steel bars of the bottom slab was decreased from φ25mm and φ16mm to φ22mm and φ14mm, respectively, achieving "equal strength replacement."

Scheme 2: The outermost load-bearing steel bars of the bottom slab were replaced from HRB400 to HRB500 high-strength steel bars, while other parameters such as steel bar diameter and distribution spacing remained unchanged, achieving "equal area replacement."

The original design scheme, which used HRB400 steel bars for the main load-bearing bars, was designated as Scheme 3. A comparative analysis and verification were conducted for the three schemes, all of which exhibited a high level of safety margin.

Since Scheme 1 not only demonstrated superior load-bearing performance compared to the original design scheme but also reduced the amount of steel bars and facilitated simpler construction procedures, it is recommended as the actual construction scheme.

At present, there have been no reports of the use of HRB600 steel bars in practical engineering.

6 Summary and Prospects

After the "Code for the design of Concrete Structures" (GB 50010—2010) was released in 2010, 500 MPa steel bars were widely used. Compared with those in Western developed countries, the strength of steel bars in China is generally between 500 and 700 MPa, and the strength of steel bars used in China is still low. In 2011, HBIS Chengsteel Co. successfully developed HRB600 steel bars, leveraging the advantages of vanadium and titanium resources. HRB600 steel bars represent a new type of high-strength steel bar. Through the application of micro-alloying technology, both the yield strength and ultimate tensile strength of the steel bars have been significantly improved, while still maintaining good plasticity and workability. At present, most domestic steel production enterprises have the technical capability to produce HRB600 steel bars. Due to the absence of specific regulations in current national standards regarding the mechanical properties of HRB600 steel bars and their parameters in reinforced concrete, the application of HRB600 high-strength steel bars in China is extremely limited. The lack of comprehensive and systematic research on the mechanical properties of HRB600 concrete components and structures, particularly foundational experimental studies, directly impedes the application and promotion of HRB600-grade steel bars in practical engineering projects.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Hu, upon reasonable request.

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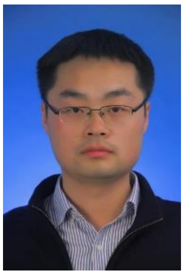
AUTHOR BIOGRAPHIES

	**Fangjian Hu** Ph.D. Senior Engineer. Shanghai Urban Construction Design & Research Institute (Group) Co., Ltd. Research Direction: Bridge Design and Research, BIM Technology R&D. Email: hufangjian@sucdri.com