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Review and Prospect of the Development of Railway Steel Structure in China

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Abstract: China has made significant progress in railway construction since the founding of its railway system more than 70 years ago. China's high-speed railway industry has developed rapidly and has become an emblem of the nation during the past 15 years. Steel structures play an irreplaceable and critical role in railway development and are widely applied in long-span railway steel bridges and roof trusses of railway stations. This research reviews the prospects for the development of railway steel structures, as well as the development of steel railway structures from the perspectives of the material, structure, and project scale, and proposes the development trends of such structures, namely, the lightness in weight, assembly, informatization, strong durability, and high tenacity. Moreover, the focus of the future development of steel railway structures is summarized in terms of the design, construction, maintenance, and materials. The diversification of application areas and environments has posed a series of technical challenges for the development of such structures, including a weather resistant design, construction in harsh marine environments, and a lack of maintenance in a plateau environment, all of which require persistent and further research.
Keywords: steel bridge; railway station; steel structure; informatization; durability; development trend

1 Introduction

As an important national infrastructure and popular means of transportation, railways are an important aspect in the integrated transportation system in China. As of the end of 2019, the operating mileage of the Chinese railway system has reached 13.9×10^4 km, including 3.5×10^4 km of high-speed railway. In a railway infrastructure, many important facilities are constructed using steel structures, including large-span railway bridges across rivers and valleys, and modern large-span elevated station buildings. The rapid development of railway infrastructure is closely related to research and development and the application of steel structure technology.

Steel structures are mainly divided into buildings and bridges. Compared with reinforced concrete structures, steel structures have the advantages of a high strength, low engineering cost, lightness in weight, short construction period, and factory production. With the rapid development of the national economy, the level of design, processing, and construction technology of steel structures has been significantly improved, and its application in railways has also been developed. China has built many large-span railway steel bridges across major rivers and large-span station buildings with novel structures and aesthetically appealing appearances, which has greatly promoted the development of the Chinese railway infrastructure [1].

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This paper reviews the development of steel structures such as long-span railway steel bridges and roof trusses of stations. According to the conditions in China, the development trends of lighter weight, easier assembly, informatization, durability, and high toughness of the steel structures used in railway infrastructure is put forward in this paper. Further, the future design, construction, operation, maintenance, and material quality of steel structures, which are based on building information model (BIM) technology using information design, assembly construction, intelligent operations, and maintenance of steel structures are suggested.

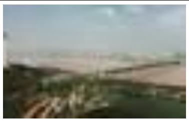
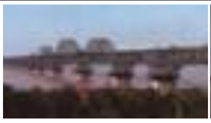
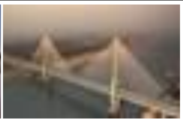
2 Review of development of steel structures of railway infrastructure in China

Focusing on steel bridges and stations in railway infrastructure, this paper reviews the development of steel structures in China from the perspectives of materials, structures, and project volume.

2.1 Steel bridges

In 1937, the Qiantang River Bridge was the first double deck steel truss bridge designed and built in China. Since the founding of the People’s Republic of China, significant achievements have been made in the development of railway bridge technology, particularly during the past 20 years. Owing to the construction of high-speed railways, several long-span bridges have been completed or started construction [1]. With the development of railway long-span bridge technologies, many milestone bridge projects have been built, as shown in Table 1 and Fig. 1.

Table 1. Representative steel bridges of Yangtze River Railway in China.

Bridge name	Wuhan Yangtze River Bridge	Nanjing Yangtze River Bridge	Jiujiang Yangtze River Bridge	Wuhu Yangtze River Bridge	Tianxingzhou Yangtse Bridge
Appearance					
Main span (m)	128	160	216	312	504
Operating load	2 railways and 4 highways	2 railways and 4 highways	2 railways and 4 highways	2 railways and 4 highways	4 railways and 6 highways
Completion time/ year	1957	1968	1994	2000	2008
Steel /($\times 10^4$ t)	2.44	6.65	5.68	7.16	4.61
Type of steel	A3q	16Mnq	15MnVNq	14MnNbq	Q370q

Note: 2 railways and 4 highways refer to double track railway and four-lane highway; 4 railways and 6 highways refer to four line railways and six lane highways.

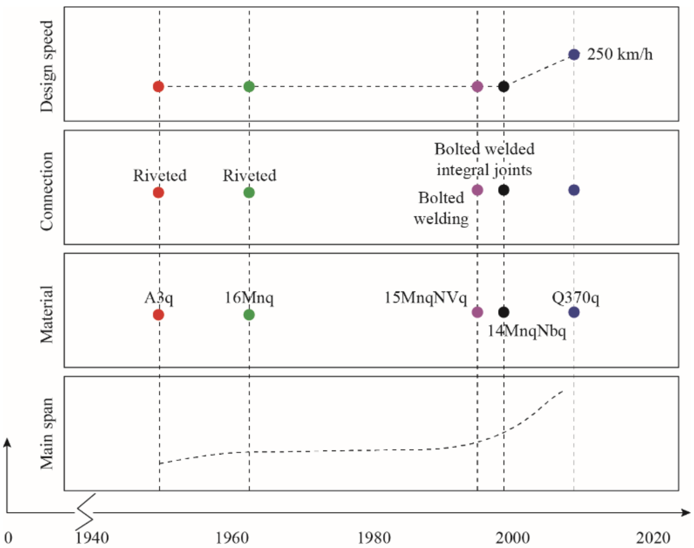


Fig. 1. Development history of railway steel bridges in China.

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The main bridge of the Wuhan Yangtze River Bridge is a riveted continuous steel truss beam with a span of 3 × 128 m, which passes through a double-track railway and a four-lane highway. The main truss was made of imported A3q steel, and the steel consumption of the whole bridge was 2.44 × 10^4 t. The steel sheet pile cofferdam was used for the first time. The diameter of the reinforced concrete pipe column was 1.55 m. The completion of the Wuhan Yangtze River Bridge marked the initial capacity of building large-span railway bridges in China.

The main bridge of the Nanjing Yangtze River Bridge is a 3 × 160 m riveted continuous steel truss girder, which passes through a double-track railway and a four-lane highway. The main truss is made of 16Mnq, independently developed in China, and the amount of steel used is 6.65 × 10^4 t. The main bridge adopted four types of foundations: island-built heavy concrete open caisson foundation, a deep-water floating reinforced concrete caisson foundation, a steel sheet pile cofferdam pipe column foundation, and a caisson plus pipe column foundation, of which the diameter of the pre-stressed concrete pipe column was 3.6 m. The completion of the Nanjing Yangtze River Bridge marked the independent innovation of railway bridge technology in China.

The main bridge of Jiujiang Yangtze River Bridge is a continuous steel truss arch bridge with a span of 180 m + 216 m + 180 m, which passes through a double-track railway and a four-lane highway. The main truss is made of 15MnVNq, which was developed independently in China. M27 high-strength bolts were used for the first time. The steel used in the entire bridge amounts to 5.68 × 10^4 t. A double-wall steel cofferdam drilling foundation was used to replace the pipe column foundation. The completion of the Jiujiang Yangtze River Bridge marked the withdrawal of the riveted steel bridge.

The main bridge of the Wuhu Yangtze River Bridge is a cable-stayed bridge with a span of 180 m + 312 m + 180 m with double pylons and double cable planes. It passes through a double-track railway and four-lane highway. The main truss is composed of 14MnNbq bridge steel independently developed by China. The entire joint was welded by a thick plate, and the amount of steel used in the complete bridge is 7.16 × 10^4 t. The composite truss beam is composed of a reinforced concrete slab and a steel truss beam. The completion of the Wuhu Yangtze River Bridge marked a significant stride in the direction of full welding for bridge technology in China, and opened the way for the construction of a railway long-span cable-stayed bridge.

Tianxingzhou Yangtze River Bridge is a highway railway cable-stayed bridge with a main span of 504 m, passing through a four-line railway and six-lane highway. Three main trusses, three cable planes, and bolt-weld combined connections were adopted for the first time globally. The material of the steel structure used is Q370q, and the amount of steel used for the whole bridge is 4.61 × 10^4 t. The completion of the Tianxingzhou Yangtze River Bridge realized the span of a railway bridge of 300–500 m in China, marking a new step in railway cable-stayed bridge technology in the country [2].

Based on the above achievements, Chinese steel bridge technology has been further developed. The main spans of the Hutong Yangtze River Bridge and the Wufengshan Yangtze River Bridge under construction both exceed 1 km. Taking the Hutong Yangtze River Bridge as an example [3], the main span of the bridge is 140 m + 462 m + 1092 m + 462 m + 140 m, with three main trusses and three cable planes. The maximum axial force of the main truss section is 7.0 × 10^5 t. According to the bearing demand, the steel truss girder of the main bridge is determined to adopt Q370qe, Q420qe, Q500qe, and other steel specifications. The total steel consumption is 13.95 × 10^4 t, of which Q500qe steel consumption is 3.16 × 10^4 t. The bridge of the main channel is designed as a fully welded integral segment, realizing large-scale and factory manufacturing of the bridge. There are 92 segments of the whole bridge, including 12 segments with a mass of 1600 t. It is composed of 372 highway and railway decks, 170 transverse couplers, 558 chord members, and 1269 web members. The maximum weight of a single member is approximately 114 t, and the highest is 5 m. The whole segment hoisting technology is used to complete the construction, as shown in Fig. 2.

2.2 Railway stations

Most railway stations were built before 1949. After 1949, some stations with different requirements were built. However, until the end of the 20th century, most of the station building structures in China were brick-wood structures or concrete structures, with small spans and single functions. In recent years, with the rapid development of high-speed railways, the construction of railway stations in China has also made significant progress. A number of station facilities with novel structures and aesthetic appearances have been constructed one after another, as shown in Table 2. Among them, the Nanjing south railway station and the Beijing south railway station are the most representative.

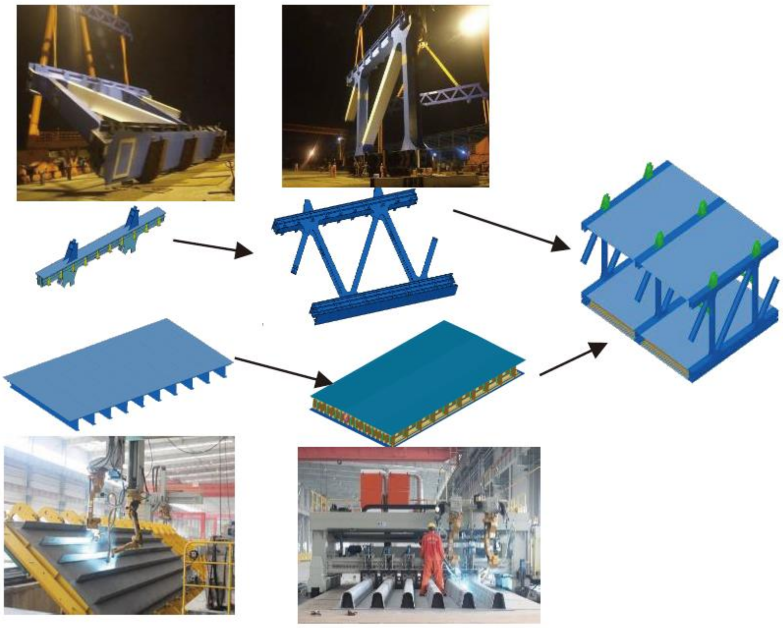
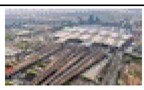


Fig. 2. Schematic of steel girder fabrication of Hutong Yangtze River Bridge.

Table 2. Representative high-speed railway stations in China

Station name	Beijing South	Shanghai Hongqiao	Guangzhou South	Nanjing South	Tianjin West	Zhengzhou East
Appearance						
Platform	13 platforms, 24 lines	16 platforms, 30 lines	15 platforms, 28 lines	15 platforms, 28 lines	13 platforms, 26 lines	16 platforms, 32 lines
Operation time	2008	2010	2010	2011	2011	2012
Steel consumption ($\times 10^4$t)	5	8	8	12	7	9

The main station building of the Nanjing south railway station adopted the frame structure of an integrated station-bridge. The first floor of the station and the second floor of the platform are large-span structures supporting the overload load. The roof truss was a large-span and large cantilever steel structure with a maximum span of 72 m, maximum cantilever of 30 m, and total height of nearly 60 m. The orthotropic steel grid structure was adopted for the station building cover, and the total steel consumption reached up to 12×10^4 t.

The main structure of the Beijing South railway station was composed of a central station building, platform awning, and underground transfer hall. The total amount of steel used was approximately 5×10^4 t. The central station building is a hyperbolic dome with an elliptical shape. The roof has a smooth curved surface with two-way circular arcs, as shown in Fig. 3. Its main load-bearing members include lattice columns, transverse trusses, longitudinal trusses, and steel beams supporting the roof [4]. The steel structure roof consists of 15 three-span continuous variable section rigid frames. The awning is equipped with 94 A-shaped steel tower columns, the maximum sag of the pre-stressed suspension beam is 6.4 m, and the inner ring curved viaduct was located between the building and awning, with a span of 16–40 m. The roof construction adopted a high-altitude scattered assembly method.

3 Development trend of steel structures

With the improvement of steel structure design and construction level, steel railway structures are being developed with lightweight, assembly, informatization, durability, and high toughness characteristics.

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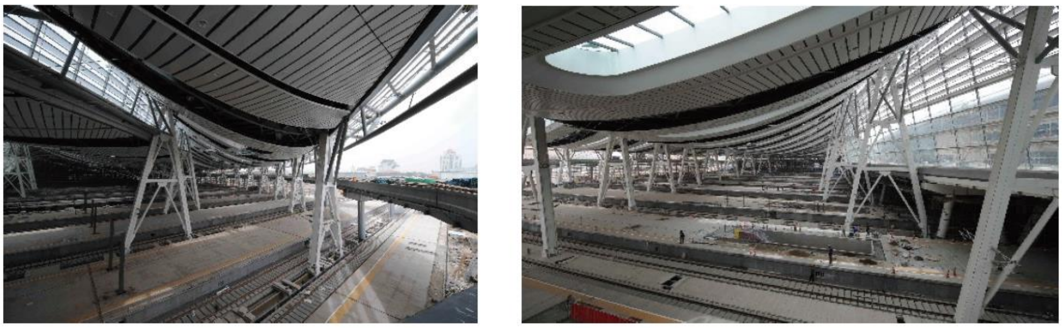

Fig. 3. Beijing South railway station during construction.

3.1 Lightweight

At present, both railway bridges and station buildings are developing toward the direction of long-span structures. This is because self-weight is an important factor that restricts the span; therefore, lightweight bridges, roof trusses, and other long-span structures are inevitable. The application of high-strength lightweight materials is one of the breakthroughs of lightweight structure technology, and steel structures, as a typical high-strength lightweight structure, will be widely used in future railway constructions.

3.2 Assembly

With the development of modern industrial technologies, the processing accuracy of prefabricated components, improvements in assembly construction technologies, and prefabricated construction have been widely used. An assembly construction can shorten the construction period, is resource intensive, reduces the construction interference, and has a factory and intensive management approach more conducive to ensuring the construction quality. Rapid construction, unmanned or less humanized construction, factory construction, and high-quality construction will be the development directions of construction technologies in the future. These technologies all require a higher degree of assembly of the steel structure, particularly the assembly of the overall structure, as shown in Fig. 4.

Fig. 4. Assembly and integral hoisting of steel beam segment of dual-purpose highway–railway bridge.

3.3 Informatization

The design and construction, engineering management, maintenance, and repair of steel structures need to be supported by modern information and communication technologies, thus involving the application of big data, Internet of Things, artificial intelligence, and other technological aspects (Fig. 5). Informatization focuses on the whole lifecycle of the design, construction, operation, and maintenance of steel structures, and includes intelligent construction processes and intelligent management decisions.

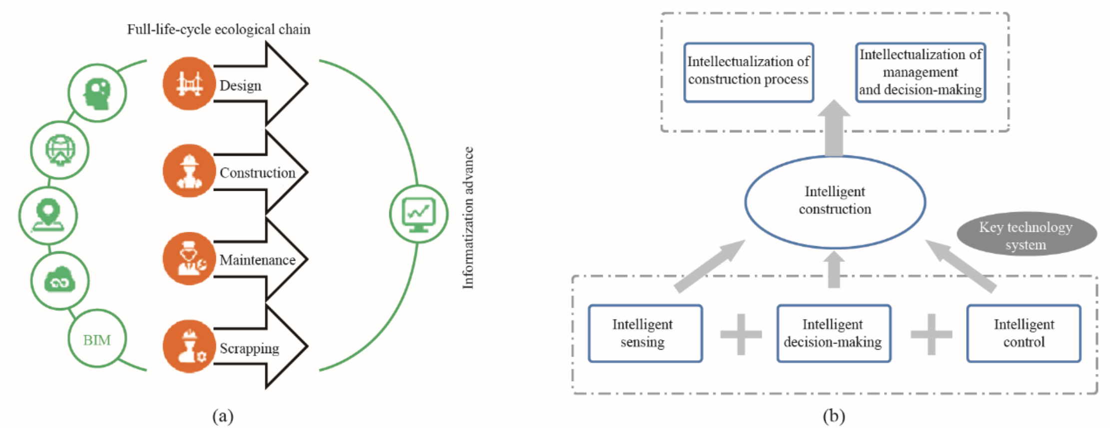

Fig. 5. Informatization and intelligent construction.

3.4 Durability

According to the Chinese bridge design code, the design life of railway steel bridges is generally 100 years. From the requirements of steel structure performance and green technology development, there has been a technical trend to continue extending the service life of steel structures. The development and application of high-performance weathering steel plates, stainless-clad bimetallic steel plates, and new coating materials and systems have become the main direction of studies on the structural durability of railway steel.

3.5 High toughness

The steel structures used in railways should resist the impact of natural disasters to a certain extent, and effectively resist intentional or unintentional man-made damage, which is not only related to the safety of the steel structure, but also to the safety of people's lives, property, and economic and social development. The steel structure must have a certain toughness. The main technical directions from the materials include focusing on the development of high-toughness steel to improve the toughness of the structural materials, and from the structural system include optimizing the structural system, particularly the structural configuration of the joints [5].

4 Suggestions on significant development of steel structures in China

4.1 Design

4.1.1 Identify service environment and verification design requirements

China has a vast territory and complex geographical, geological, and climatic environments. Railway infrastructures are distributed throughout the country. In the design procedure, it is necessary to accurately judge the service environment of steel structures. For example, the special situation of the Qinghai-Tibet Plateau should suggest new service environment classification and requirements, allow corresponding construction requirements and suggestions to be applied, and make a solid foundation for the of durability steel structures. In addition, earthquakes, floods, debris flows, landslides, and other natural disasters in the service area of steel structures should be fully investigated and clearly classified. Appropriate design standards should be accurately considered to reasonably determine the initial conditions for the resistance of the steel structure. Taking earthquake disasters as an example, the seismic performance requirement, design method, structural measures, and fortification standards of railway steel bridges should be defined according to local conditions.

4.1.2 Advance design theories and methods

At present, the more mature methods of steel structure design include the allowable stress method and limit state method, but from the perspective of improving structural performance and reducing cost, there is still room for improvement in relevant design theories and structure systems. As for the design theories, it is necessary to summarize and advance research on the stiffness control standards of long-span bridges, and systematically study the control standards and related technology of temperature, creep, and other late deformation. As for the structural system, it is appropriate to conduct technical research on pre-stressed beams, cable-stayed suspension cooperative structure systems, and new steel-concrete composite structures [6]. Light structural systems, light tubular, and

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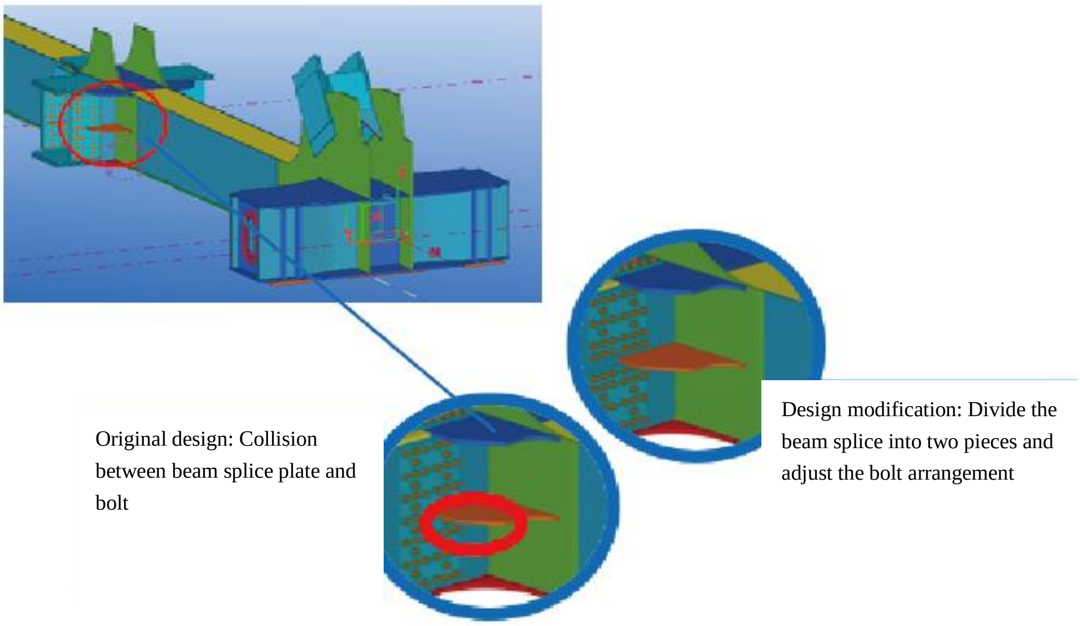
rectangular open web members can also be suggested. Advancing new computational algorithms and developing new software is also an important aspect to promote and guarantee the innovation and development of steel structure design theories and engineering capacity.

4.1.3 Extend the application of BIM Technology

BIM technology is used to realize information sharing and management. It has been optimized in the design procedure, which is more reasonable for the implementation of the project. It can effectively prevent “errors and missing collisions” in the design, and provide a powerful means for the digitization of engineering construction and maintenance, as well as a visualization of the procedure management, thereby greatly improving the efficiency of the design and audit, as shown in Fig. 6. We should promote the application of BIM technology in the design of railway steel bridges and improve the information level of the bridge design and management in China [7].



Collision between beam splice plate and bolt

Fig. 6. BIM technology solving collision problem.

4.2 Construction

4.2.1 Geometrical control

At present, most steel structures are statically indeterminate. During the process of installation and construction, if the geometrical control is not strict, it can produce distortion and bending deformation, the distortion and bending deformation might induce additional internal forces and change the stress state, and in serious cases, the structures can be damaged. During the process of steel structure installation and construction, we should pay attention to the use of advanced surveying, mapping, and adjustment technology to ensure an alignment.

4.2.2 Welding

Historical experience has shown that the quality problems caused by welding defects (non-compact, with a poor connection, incomplete penetration, slag inclusion, incomplete welding) occur during the welding process of steel structures, which affects the capacity and durability of the steel structure. At present, automatic submerged arc welding and gas-shielded welding are mainly used in the construction of steel structures, and the fundamental technology has become extremely mature. To meet the welding requirements of some special steel structures, advanced welding processes, equipment, and software should be developed, as shown in Fig. 7. Such advancements should be demonstrated and applied, and the experience should be summarized and comprehensively promoted.

(a) Automatic assembly and positioning machine for U-shaped rib unit

(b) Welding robot for steel bridge deck plate

Fig. 7. Advanced welding technology of railway steel structure.

4.2.3 Painting

If the coating method is improper and the spraying quality is insufficient, the corrosion of the railway steel structure will be aggravated. From the analysis of the field situation, if the rust removal method is backward and the effect of rust removal is poor, direct coating will seriously affect the coating quality.

It is necessary to popularize factory rust removal and coating methods, popularize on-site bolt connection methods (to avoid welding damaging the factory coating), and comprehensively guarantee the coating quality through technical upgraded.

4.2.4 Development of factory equipment

Construction equipment suitable for the assembly of large-scale railway steel structures as well as the support of factory process equipment and intelligent equipment thereby gradually realizing an automatic construction should be developed. At the same time, this can reduce or avoid the influence of artificial random behavior on the construction quality of steel structures.

4.3 Operation and maintenance

4.3.1 Detection and monitoring

In addition to daily inspections, long-term monitoring equipment should be set up to carry out real-time monitoring of the environmental characteristics and structural status during operation. Dynamic detection equipment is used to regularly detect the key structures, and a comprehensive analysis of the monitoring data is carried out to accurately guide the maintenance and evaluation of the structure, thereby ensuring the safe and reliable bearing capacity of a steel structure during its service life.

4.3.2 Repair

In the face of structural damage caused by natural disasters and man-made destruction as well as defects or hidden dangers in the design and construction, maintenance decisions should be made in a timely manner to guide the use of new technologies and materials for repair, so as to eliminate the phenomenon of "defective work" of railway steel structures. Taking the fatigue reinforcement and repair of an orthotropic bridge deck as an example, the combination of a steel plate and high-strength bolt or a high-performance concrete pavement can be used to repair structural defects, as shown in Fig. 8.

4.3.3 Assessment

Based on the monitoring data, the state evaluation and service performance analysis of railway steel structures are carried out, and the change process of the structural performance state is mastered. For steel structures that have been used for many years or suffer sudden damage, a service life assessment should be carried out to ensure absolute safety.

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(a) Steel plate + high strength bolt reinforcement (b) High performance concrete pavement reinforcement

Fig. 8. Strengthening forms of orthotropic deck fatigue.

4.4 Steel

The performance of the steel is the source of the steel structure performance, and improving the smelting technology to ensure the qualification rate of the steel is the top priority. Based on the quality assurance of steel, further improving the performance of steel is a key direction for improving the performance of railway steel structures in the future.

4.4.1 High strength

At present, Q345 and Q370 bridge steel types are widely used in domestic railway bridges, whereas Q420q and Q500q steel are in the stage of popularization. For example, a Q420q steel plate was used for the Dashengguan Yangtze River Bridge in Nanjing, and Q500q steel with a higher strength grade was used for the Hutong Yangtze River Bridge. It is considered that a yield strength of less than 500 MPa and a tensile strength of less than 630 MPa should be met in both horizontal and vertical tensile tests [8]. With the construction of long-span bridges, the application demand of high-strength steel in railway infrastructures will continuously increase. Bridge steel with Q500q specifications and a cable steel wire with a strength of above 2000 MPa will be indispensable.

4.4.2 Weather ability

Corrosion consumes a large amount of steel resources, resulting in natural environmental pollution and ecological environmental damage, of which infrastructure corrosion accounts for a considerable proportion. It is necessary to strengthen the research on steel that is not corroded or corroded by chemical harmful substances, and the cost of the problem should be given focus. Owing to the increase in the smelting process, the one-time investment of weathering steel is slightly higher than that of ordinary low-alloy steel of the same grade. However, from the perspective of bridge finished products, owing to a reduction of the surface treatment and coating of the components in the factory and on site, the comprehensive economic benefits are greater [9].

4.4.3 Toughness

Railway infrastructures require high-quality structural steel that not only meets the strength requirements but also has a high toughness. To improve the toughness of railway steel bridges and prevent safety accidents caused by a brittle fracture, the toughness of a bridge steel will continuously improve. The brittle fracture of steel is more likely to occur in cold areas at high elevation, which puts forward higher requirements for the toughness index of the materials. While continuously improving the strength of the steel, it is extremely important to maintain certain fracture resistance by improving the toughness.

5 Conclusion

With the continuous increase of railway lines in China, an increasing number of railway steel structures are being applied under special climate conditions such as strong marine corrosion, cold temperatures at high plateaus, and strong ultraviolet exposure, which incurs higher requirements for the design, construction, operation and maintenance, equipment, and steel materials of such structures. A series of technical problems need to be solved, such as weather resistance design, construction in a harsh marine environment, and less maintenance of the plateaus.

Aiming at the problem of weather resistance, it is important to continuously improve the performance requirements of weathering steel plates and weathering bolts, and to increase the application of weathering steel in railway infrastructures. In view of a harsh construction environment, the development of assembly, mechanization, and intelligent construction technology can reduce the amount of on-site construction operation and improve the construction quality. Aiming at the problems of plateau maintenance, the operation and maintenance management level of steel structures should be improved, and new intelligent and digital management and maintenance technologies and equipment should be developed.

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