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Status Quo and Development Trend of Lightweight, High-Strength, and Durable Structural Materials Applied in Marine Bridge Engineering

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Abstract: This study focuses on the requirements of long-span marine bridges in achieving durability and a light weight. According to a thorough investigation of lightweight, high-strength, and durable materials, the research status and development tendency of high-performance steel, high-performance concrete, and fiber-reinforced polymer are examined. The application technologies of such materials for the key zones of bridges are introduced, and strategic recommendations are proposed for the development of lightweight, high-strength, and durable structural materials in marine bridge engineering. The research results will help satisfy the requirements of marine bridge engineering in terms of high performance, long life, and light weight, and improve the durability and span of long-span bridges in marine environments.

Keywords: marine environment; long-span bridges; high-performance steel; high-performance concrete; fiber-reinforced polymer (FRP)

1 Introduction

The coupling effects of a harsh environment and complicated loads (e.g., from wind or vehicles) lead to serious deficiencies in the long-term serviceability (e.g., durability degradation caused by fatigue and creep) of marine bridge structures, seriously affecting their safety and service life. Steel suffers from serious degradation of its mechanical properties. The economic loss caused by steel corrosion reached 1900 billion CNY in 2014, which accounted for 3% of the gross domestic product that year. Additionally, concrete structures under water or in areas with fluctuating water levels are directly exposed to corrosive elements in seawater, such as sulfates and magnesium salts. Sulfate ions react with hydrated aluminate and calcium hydroxide. Moreover, magnesium sulfate incurs a decomposition of calcium silicate hydrate gel in cement, leading to a strength loss and a decrease in the bond performance. Over 50% of the construction budget in Europe is spent on the repair and renovation of concrete structures [1]. The maintenance cost of concrete structures in highway and bridge engineering projects has been estimated as 10 billion CNY in China [2]. Furthermore, the high stress applied to bridge cables accelerates the corrosion. For example, on the Maracibo Bridge, which was constructed in Venezuela in 1960, hidden problems were found in 25 of the 192 steel cables exposed to the impact of wind and rain coupled with violent vibrations. Such damage was not discovered and repaired in a timely manner, and one cable ruptured in

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1979, leading to a partial collapse of the bridge and a large loss of up to 50 million USD. Furthermore, owing to a sag effect of the cables, the effective span of a steel-cable-stayed bridge can only reach 1300 m. Steel cables fail to satisfy the requirements for the construction and economic performance of spans over 1300 m.

Focusing on the deficiencies in the long-term serviceability of long-span bridges in a marine environment and the requirements of light weight, an investigation was conducted on lightweight, high-strength, and durable materials. On the basis of the results, the application methods of these materials in key bridge zones were studied, and bottlenecks regarding the durability and span of offshore long-span bridges will be broken, targeting a high level of performance and longevity. The relevant technologies include those targeted at the advancement of conventional steel and concrete and the application of novel fiber-reinforced polymers (FRPs) used in marine bridges.

2 Status quo and development trend

2.1 Status quo and development trend of high-performance steel

2.1.1 Overview of existing studies

The yield strength of steel used for marine bridge engineering abroad ranges from 245 to 700 MPa [3]. The development of steel for bridges in China started in the 1950s and 1960s, and the development has been slow compared with that in other countries. Shanghai Nanpu Bridge, Yangpu Bridge, and Xupu Bridge, which were built in the 1990s, all adopted imported or domestic StE355 steel. Subsequently, the bridge steel 14MnNbq was developed in China, which has been used in nearly 20 bridges, such as the Wuhu Yangtze River Bridge, Nanjing Yangtze River Bridge, and Changdong Second Bridge of the Yellow River. In 2007, bridge steel WNQ570 (Q420qE) was used in the Nanjing Dashengguan Yangtze River Bridge, and in 2016, the high-performance bridge steel Q500qE was first used in the Shanghai-Nantong Yangtze River Bridge (Fig. 1).

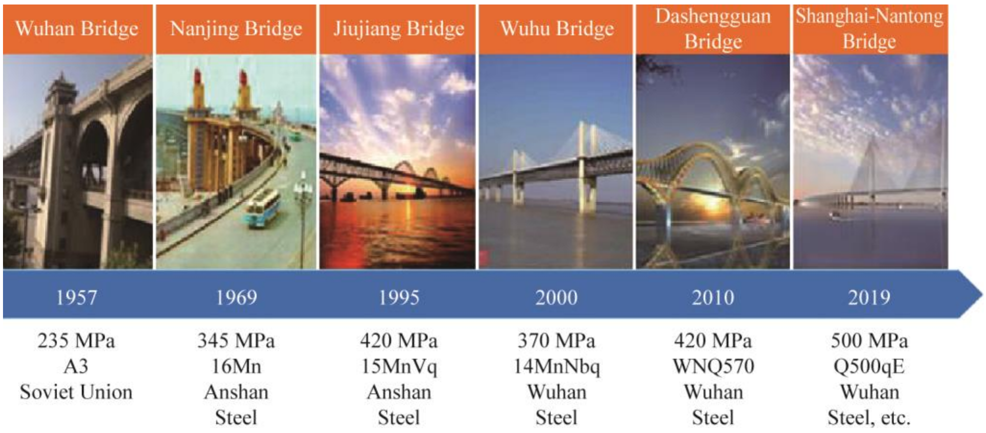

Fig. 1. Development history of Chinese steel used in bridges.

(1) Surface treatment technology for corrosion resistance in steel

As coatings were used for steel bridge protection in the 18th century, the technology of steel surface treatment has a history of more than 200 years. With regard to coating materials, Zn-rich coatings and sprayed metal coatings with both isolation and electrochemical sacrificial anode protection are currently used as primers, and the corrosion protection of steel structures can be divided into the following two categories. (1) Zn-rich coatings and epoxy mica-iron coatings are used as primers and intermediate coatings, respectively. Alkyd resin coatings, chlorinated rubber coatings, and polyurethane (including aliphatic) coatings are used as top coatings. (2) To form a long-term anti-corrosion system, sprayed metal coatings and fluorocarbon coatings are used as primers and top coatings, respectively. At present, the advanced surface stabilization technologies used abroad include weatherability coating treatment, oxide coating treatment, rust coating treatment, rust layer stabilization surface treatment, and titanium alloy surface treatment.

After a surface treatment technology is applied once, the maintenance-free time increases. However, the application of these technologies in steel components is still lacking in China, and there are no mature technologies available to treat the surface rust layer of stable weatherable steel components.

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(2) Corrosion-resistant steel

As a type of stainless steel, corrosion-resistant steel has been popularly applied to bridge structures and appears in approximately 50% and 20% of the bridges in the USA and Japan, respectively. Additionally, 90% of newly constructed steel bridges in Canada are manufactured using corrosion-resistant steel, and more than 10 corrosion-resistant steel bridges are now used in South Korea. The Cu-P-Cr-Ni class of Corten® steel from the USA and SMA® steel from Japan are globally accepted types of corrosion-resistant steel [4]. Apart from imitations of the aforementioned foreign products, manufacturers in China have gradually developed the Cu-P-RE class of corrosion-resistant steel, considering the absence of Ni/Cr resources and the abundance of rare-earth resources in China. In 1984, the standards for superior atmospheric-corrosion resisting structural steel and corrosion-resistant steel suitable for welded structures were published in China. They were later revised in 2008. Recent years have witnessed the growing application of corrosion-resistant steel in domestic bridges, mainly including the Weihe River Highway Bridge in Xianyang, the Houdingxiang Bridge in Shenyang, the Road No. 16 Sea-crossing Bridge in Dalian, the Grand Bridge of the Guanting Reservoir, the Yarlung Zangbo River Bridge along the Lalin railway of the Sichuan–Tibet line, and road/bridge engineering projects in Hebei province. Indoor accelerated corrosion tests of domestic corrosion-resistant steel, such as Q355NH, Q345qNH, Q420qNH, Q460qNH, Q420qE, and Q500qE steel, have been conducted, along with long-term exposure tests. Studies have indicated that the aforementioned types of steel have excellent corrosion resistance, i.e., over 2–8 times that of normal Q235 steel.

Nevertheless, there remains a lack of engineering applications of the above corrosion-resistant steels under exposure and in marine environments. For the vast majority of marine bridges in China, covering treatment is employed as the major corrosion protection method. In contrast, in advanced countries, corrosion-resistant steel with a high level of performance is applied in bridges in marine environments, and unified standards with regard to the material selection, covering adoption, exposure application, and surface treatment have been established; however, China lags in these aspects.

(3) Weathering steel

Weathering steel is a type of low-alloy steel as an intermediate between normal and stainless steel. In Japan, a series of weathering steel types with strengths of 355 and 455 MPa have been developed for bridges in severe marine environments. Weathering steel has been widely employed in Japan's marine bridges, including S490A/B/C, SMA490AW/BW/CW, and SMA490AP/BP/CP steel, which has significantly reduced the lifecycle cost of the bridges. Through engineering practice, the application and maintenance technologies of weathering steel have advanced considerably.

Steel enterprises in China have also moved toward investigating weathering steel for bridge applications. By taking ultralow-C bainite as a core object, the multiphase microstructures of weathering steel are homogenized and refined using HPC, RPC, and TMCP techniques. By controlling the C content to within 0.03%–0.07% and optimizing the proportions of Cu, Ni, Cr, Mo, Ti, and Nb, the toughness of this type of steel is enhanced, and its sensitivity to cold cracking and the hardness of the heat-affected zones can be reduced. Through regulations on the microstructural transition of ferrite and bainite, the strength, plasticity, and toughness of the steel are improved. Similarly, through well-distributed ferrite and bainite and optimized proportions of Cu, Ni, Cr, and Mo, the steel can be endowed with a superior resistance to atmospheric corrosion.

Despite the low cost, ease of production, and effectiveness in retarding corrosion, it requires a long time (4–15 years) to form a compact rust layer for weathering steel. Prior to the formation of a stabilized rust layer, the rusty liquid can flow, spatter, and volatilize, which pollutes the surrounding environment. In the case of coastal marine atmospheric conditions, stratiform spalling can occur in weathering steel. Additionally, domestic weathering steel has the following shortcomings: inadequate weathering properties and toughness at low temperatures, inadequate welding behaviors and corrosion resistance of the closing zone, and high integrated costs.

(4) High-Ni steel

High-Ni steel has good comprehensive properties and is resistant to various types of acid and stress corrosion. Japanese studies on high-Ni steel are at the forefront of global research. The Ni content in Japanese products exceeds the upper limit of the relevant standards of JIS, GB/T714, and ASTM709. A typical highly corrosion-resistant steel containing Ni is applied. The superior corrosion resistance of high-Ni steel in Japan was verified via atmospheric exposure tests of high corrosion-resistant steels with different Ni contents in a high-salt environment (salt content of up to 1.3 mdd in air).

Compared with Japanese JIS standard-compliant corrosion-resistant steel and ordinary steel under the same corrosion conditions, high-Ni steel has exhibited a smaller thickness reduction, making it far superior to ordinary steel, and has excellent corrosion resistance. However, owing to the high content of precious alloying elements, the initial cost of high Ni steel is extremely high, and the material lacks long-term application data.

(5) Steel for cable ropes used for marine bridge engineering in China and abroad

An SWRS87B-DLP wire rod produced using Japan's direct in-line patenting (DLP) process has a good tissue uniformity and can satisfy the requirement of φ5.0 mm at 2000 MPa (including torsion). Europe's main steel mills specializing in high-C steel production are British Steel and Germany's Saarstahl Co. In contrast, the bridge cable industry in South Korea is less than 10 years old and mainly uses the traditional treatment method of a wire rod offline Pb bath to solve the problem of the uniformity of the wire rod.

The steel used for domestic bridge cables mainly adopts a Zn-Al steel wire, which is characterized by a high strength, low slack, good linearity, good cable formability, and reduced creep in the steel wire after service. Galvanized steel wire companies no longer purchase Japanese DLP wire rods; thus, steel mills in China have more opportunities to continuously improve their wire-rod quality [5]. Domestic Zn-Al alloy-coated steel wires have been used in more than five bridges. For example, in 2007, the Sutong Bridge adopted a φ7.0-mm 1770-MPa-grade bridge wire. With the increase in urbanization construction, particularly the construction of urban agglomerations along the Yellow River, Yangtze River, and Pearl River, and the launch of the overseas infrastructure market under the background of the Belt and Road initiative, it is expected that the application scope of Zn-Al alloy plating technology will become extremely broad.

The increase in strength achieved by increasing the C content causes the plasticity of the wire rod to decrease significantly. The torsion, bending, and winding properties of a high-strength steel wire present significant challenges. Additionally, the winding bending torsion characteristics, process performance, and strength index of bridge cables have yet to be studied in detail. Moreover, the technical protection of foreign wire products makes the localization of related technologies extremely urgent.

2.1.2 Development trend

According to the present situation of steel for bridge use, high-performance steel has become the main direction of future development. Research and engineering practice have shown that high-performance steel for bridge structures has the following advantages: a reduction in weight, easy handling and transport, and a reduction in the bending moment of the cantilever section in incremental launching construction, reducing the construction and transportation costs. Additionally, the beam height can be reduced to make the structure more decent. Moreover, an increase in the span and a reduction in the number of piers or main beams can be achieved. The manufacturing cost for the welding is also reduced, and because the thickness of the plate is reduced, the welding volume is reduced, as is the preheating requirement. Furthermore, the improved fracture toughness reduces the possibility of sudden damage caused by a brittle fracture, increases the fracture tolerance, and improves the safety factor and reliability of the structure. The high corrosion resistance of high-performance steel allows the bridge to be free from coating during long-term use. Finally, the service life of the bridge is extended, and the costs of the bridge are reduced.

The future development trend of anti-corrosion coating technology for use in bridges will follow the principles of high performance, long life, and environmental protection. It will also be diversified to adapt to different corrosive environments and anti-corrosion parts and should consider the construction technology and maintenance plan, as well as the material costs and landscape requirements.

2.2 Status quo and development trend of high-performance concrete

2.2.1 Overview of previous research

Durability, fluidity, and volume stability are important factors in ensuring the high performance of concrete.

(1) Surface protection technology

External protection technologies for concrete can be divided into coating, hole blocking, water-repellent hole walls, and pore structure optimization according to the different mechanisms applied. Surface protection materials include organic and inorganic materials. Among the different organic protective materials, the polyurea elastic coating is an advanced, solvent-free, non-polluting coating developed to satisfy the needs of environmental protection. It was developed after traditional coatings such as high-solid coatings, waterborne coatings, photocurable coatings, and powder coatings. This highly elastic thick film coating allows not only one-time spraying of thick coatings but also fast curing, excellent mechanical properties, and chemical resistance. Compared with organic coatings, inorganic protective materials have the advantages of wide sources of raw materials, low

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cost and energy consumption, easy transport and storage, good aging resistance, environmental protection, high temperature resistance, and good gas permeability. At present, the main bottlenecks of surface protection technology are aging and poor adhesion of the wet base surface, which are expected to be solved by a nanomodified organic coating system in the future.

(2) High-compactness concrete

Regarding the densification of concrete structures, the traditional method mainly uses concrete with a strength grade above C40, and a mineral admixture such as fly ash is introduced into the concrete mix design to achieve densification of the concrete structure. Additionally, in the case of corrosion-resistant cementitious materials, anti-sulfate cement is mainly used. By reducing the content of C_3A and $Ca(OH)_2$ in Portland cement, the risk of a corrosive reaction caused by aggressive media in the concrete material is reduced, improving the solidity of the concrete.

Recent research has revealed that nanomaterials can significantly improve the concrete compactness and erosion resistance. Based on the pore filling, the self-characteristics of the nanomaterials also contribute to the optimization of the impermeability and erosion resistance. A reasonable compounding of nanomaterials with other mineral admixtures and chemical admixtures can further enhance the durability.

(3) High-fluid concrete

The concept of high-fluid concrete was first proposed by Professor Okamura of Japan in 1986. After 1995, countries around the world gradually conducted research in this area. After more than 20 years of development, high-efficiency water reducing agents (such as sulfamic acid-based water reducing agents) have been developed for high-fluid concrete, which can greatly reduce the yield shear stress in the rheological equation of concrete materials and achieve high fluidity. Additionally, the mineral admixture types (fly ash, slag, etc.) of high-fluid concrete are optimized through a series of tests, and the aggregate size and sand content are optimized. High-fluid concrete has been applied in the final joint of the immersed tunnel of the Hong Kong–Zhuhai–Macao Bridge, which successfully solved the problem of concrete vibrations in the main joint structure.

(4) Concrete shrinkage mitigation technology

The high content of cementitious materials and low water cement ratio of high-strength and ultrahigh-performance concrete (UHPC) materials used in marine bridges leads to a large shrinkage deformation and an increased hydration temperature, resulting in a poor volume stability and a high risk of cracking. Shrinkage mitigation technology has two main uses: reducing the concrete temperature shrinkage and reducing the drying and plastic shrinkages. With regard to reducing the concrete temperature shrinkage, it is optional to use mineral admixtures such as low- or medium-heat cement or a large amount of fly ash to prepare the concrete; add admixtures with water reduction, retardation, air entraining, and expansion; and choose highly graded aggregates. With regard to reducing the dry and plastic shrinkages, expansion and curing agents are mainly used to compensate for concrete shrinkage, thereby reducing the number of microcracks in the concrete, optimizing the pore structure of the concrete, reducing the porosity, and improving the structure and performance of the interface transition zone between the cement and the aggregate [6]. In concrete shrinkage mitigation technology, it is important to further study the entire staging process to regulate the hydration heat release process of the concrete and add an expansion agent to mitigate the shrinkage.

2.2.2 Development trend

(1) Microstructure optimization technology for marine concrete

Owing to the relationship between concrete microstructure and permeability, and according to the key durability design indicators and microstructure design parameters applicable to corrosion-resistant high-performance concrete in a marine environment, high-performance concrete water reducing admixtures are adopted through the application of a concrete mix design method based on the microstructure. Auxiliary suitable functional concrete admixtures are also used. Therefore, the resistance to the medium permeability and the corrosion resistance of the concrete are significantly higher than those of ordinary concrete.

(2) External protection technology based on high weather resistance, low medium permeability, and long life

In view of the high ultraviolet radiation characteristics of a concrete structure in an atmospheric marine environment, inorganic protective materials are used to achieve hole blocking in the concrete surface layer with low shrinkage and a high crack resistance. Aiming at the problem of alternating wet and dry and wave washing in the splash zone, the sealing and protective effect of the concrete surface coating technology is realized via spraying of a polyurea elastomer with excellent wear resistance and anti-corrosion properties. Additionally, FRP wrapping technology or steel pipe composite pile technology may be considered for reinforced-concrete (RC) beams and columns exposed to the splash and tidal zones. The corrosion resistance of FRP or the protective layer of a steel pipe can effectively delay the corrosion of steel bars and the damage to concrete in concrete structures. For reducing the probability of corrosion damage of concrete structures in underwater areas, a permeable template cloth technology is used to optimize the surface pore structure of the corrosion-resistant concrete and improve the durability of the concrete structure.

(3) Organic rust-prevention technology

In view of the unique erosion environment of the ocean, a migration corrosion inhibitor is applied to the high-performance marine concrete to improve the critical chloride ion concentration on the steel surface and to comprehensively consider the corrosion resistance, mechanical properties, construction process performance of the reinforcement, and economic and other factors. A self-migrating corrosion inhibitor, as an emerging steel rust-resisting technology, has significant advantages in terms of its application.

(4) UHPC

UHPC is characterized by its high strength, toughness, and durability and is representative of the new system for achieving an increased development of cement-based materials. Nanoparticles rich in chemically active substances are efficiently obtained from industrial solid waste or low-grade resources, and as an “ecological nanomaterial,” ecological nano-UHPC with ultrahigh strength, ultrahigh toughness, and ultrahigh durability is prepared. UHPC can satisfy the urgent needs of major or special projects such as long-span bridges, thin-walled structures, anti-explosive structures, and deep water offshore platforms and has significant theoretical and practical applications for the improvement of lightweight concrete beams and slab systems, as well as the promotion of high-strength steel and the efficient use of solid waste [7].

2.3 Status quo and development trend of FRP

2.3.1 Overview of existing studies

FRPs mainly refer to continuous FRPs in civil engineering. They are produced using fibers impregnated in a resin matrix and have a specific configuration after curing. The types of fiber include C, aramid, glass, and basalt fibers, and the types of resin matrix include epoxy, vinyl, and unsaturated polyester. FRPs are categorized as carbon FRP (CFRP), aramid FRP (AFRP), glass FRP (GFRP), basalt FRP (BFRP), or hybrid FRP (HFRP) [8], depending on the fiber type. FRPs possess several common characteristics, such as lightness, high strength, and high corrosion resistance, but also have unique mechanical, physical, and chemical properties; e.g., CFRP has an extremely high strength and high elastic modulus, whereas BFRP and GFRP have good ductility. Regarding the products formed, FRPs can be divided into sheets (cloth or laminate), bars (smooth or ribbed surfaces), tendons (parallel or stranded), profiles (with a specific cross-section configuration such as tubes or H-shape), and grids/textiles, as shown in Fig. 2. Sheets are mainly employed in the strengthening of girders, bridge decks, and piers. Bars can be used as a reinforcement in the concrete of bridges or in structural strengthening. Tendons have potential use for cables in cable-stayed or suspension bridges and can also be used in strengthening through a prestress process. Profiles can serve as bridge decks or can be combined with concrete as composite bridge decks or piers. Finally, grids are commonly used in the strengthening of bridge decks and piers. Reinforcement in piers is another application of grids, which provides a considerable confinement effect and enhances the mechanical behavior and durability of the structure.

2.3.2 Development trends

(1) FRP with high durability and low cost

Conventional FRPs applied in civil engineering include CFRP, AFRP, and GFRP. CFRP has the smallest weight and highest strength, with satisfactory long-term behavior and durability, but it is expensive, which limits its large-scale applications in civil engineering. AFRP has an excessive long-term creep deformation and an extremely high cost. In contrast, GFRP has the lowest cost among the three types of FRPs but has a relatively low strength and elastic modulus, as well as poor durability in alkali materials. Focusing on the aforementioned deficiencies in conventional FRPs, several novel types of FRPs have been developed, among which BFRP has been promoted in recent years owing to its advantageous cost performance [9–11].

(2) Secondary-processable FRP products

Conventional FRPs made using a thermosetting resin cannot be further processed on the spot according to the requirements of the construction. Thus, prefabrication is necessary for FRP stirrups or other specially shaped bars. Thermoplastic resin can realize a secondary FRP process and is a convenient construction material. Polypropylene and polyethylene resin are mainly adopted as matrices in thermoplastic FRP. These two types of resin are characterized by brittleness, low strength, and poor bonding to fiber.

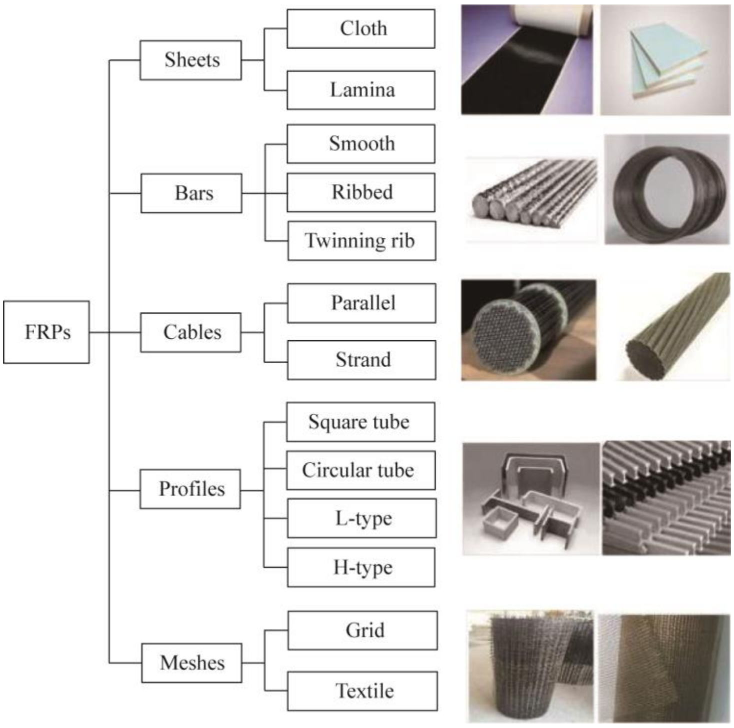

Fig. 2. Typical FRP products applied in civil engineering.

3 Application of high-performance materials in marine engineering

3.1 Application of high-performance steel in marine engineering

3.1.1 Welding technology of high-performance steel plate in marine bridge engineering

According to JIS3114, Japan developed the high-performance steels SBHS500W and SBHS700W for bridges. SBHS700W is a material used for rigid girders and was designed by Nippon Steel Cooperation in 1994 for the Akashi Kaikyo Bridge. Studies on the welding process of high-performance steel sheets for marine bridge engineering in China remains in its infancy owing to a lack of parent metal research. However, the welding process of bridge steel with good mechanical properties and the corrosion resistance of Q420qE and Q500qE are extremely mature and have been tested through practical applications [12]. Once high-performance marine corrosion-resistant steel is developed, the welding process must be rapidly developed.

3.1.2 Heat treatment process of steel wire rod used in cables

Wires (wire rods) are needed in the production of galvanized Al alloy steel wires for foreign bridge cables, which are generally made of eutectic or hypereutectic steel. To achieve high-performance cable wires with high strength, high-C steel must be endowed with good comprehensive properties through proper heat treatment. Wrestling is one of the key processes in the production of high-C steel wire. With wrestling, the wire rod can have an organized structure satisfying the requirements of the production process and various products, such as good drawing properties and comprehensive mechanical properties [13].

3.1.3 Study on deep processing technology of steel wire rods for use in cables

(1) Surface treatment of wires

To reduce the friction coefficient between a steel wire and a die wall during the drawing process and ensure the surface quality of a steel wire, the surface treatment of the wire rod should be performed before the drawing of the wires (including surface cleaning treatment, mainly to remove the oxide skin covering the surface of the wire rod) and lubrication coating treatment.

(2) Wire drawing

The main purpose of wire drawing is to obtain a steel wire with a stable shape, size, and performance index and satisfy the technical requirements of the product. The maximum extension value of deformed metal without brittle fracturing is called the cold working limit of the metal. The raw material of a galvanized Al alloy steel wire for bridge cables is hot-rolled with a high degree of sorbitic treatment, and its cold working limit is >90%. Multi-mode continuous drawing and a low partial compression ratio are adopted in practical production, avoiding the abnormal phenomenon of a temperature increase caused by an excessive deformation of the steel wire and ensuring the high strength and toughness of the steel wire.

(3) Study on fatigue resistance of steel wires

Owing to the cumulative effect of monofilament fatigue throughout the entire cable, the fatigue resistance decreases with an increase in the diameter of the main cable strand. Based on the results of the above-mentioned investigation, the factors affecting the fatigue properties of ultrahigh-strength and large-specification cable strands (such as the fatigue resistance of the raw materials and the parameters of the anchoring transition zone) are systematically analyzed and studied. According to the requirements of a high stress range of cable strands, the upper limit of the fatigue stress of a steel wire is 0.45 times the tensile strength, and the number of stress cycles achieved is 2 million.

3.2 Application of durability improvement technology of high-performance concrete in marine engineering

3.2.1 Temperature regulation, shrinkage mitigation, and toughening technology of concrete

(1) Control technology of concrete hydration heat-release process

To suppress the temperature shrinkage of the concrete, the temperature increase of the concrete must be strictly controlled. In addition to the traditional methods, such as reducing the cement dosage, heat release, and water cooling, among other factors, it is also possible to control the temperature increase of a concrete structure through chemical admixtures (hydration heat regulation material, TRI), thereby reducing the risk of cracking.

(2) Stage-by-stage whole-process concrete-shrinkage suppression technology

An amphiphilic polymer (polystearyl methacrylate) with hydrophilic and lipophilic properties was synthesized using phase-transfer catalysis, which solved the defect of a weak van der Waals force between small molecular amphiphilic compounds. Thus, the arrangement density and stability of a monomolecular film can be effectively improved, and the effective improvement of the water evaporation performance of a monomolecular film is realized. This can reduce the water evaporation during the plastic phase of concrete by >70% and reduce the plastic shrinkage by >50%. The technology has been applied to major national projects such as the Lanxin High Speed Railway, Chenggui High Speed Railway, Taizhou Bridge, and Hengqin Second Bridge.

3.2.2 Erosive medium transmission and concrete corrosion inhibition technology under alternating dry and wet phases

(1) Erosive ion transport suppression technology

A new aggressive medium transmission inhibition technology for concrete can solve the problem of traditional material dissolution by utilizing new organic matter that can form a bond with the cement hydration products. This type of product can realize a chemical bond between the hydrophobic long C chain and the cement hydration product and does not affect the hydration or strength development of the concrete. Additionally, the “nano effect” is used to further reduce the harmful pores of the concrete, optimize the pore structure, and increase the compactness of the concrete. The erosive ion transport suppression technology of Jiangsu Sobute New Materials Co., Ltd. is a typical case. By incorporating an erosion medium transmission inhibitor, the concrete compressive strength is increased by 10 MPa, and the electric flux, water absorption rate, and chloride ion diffusion coefficient are reduced by >40%, with the overall effect increased by 50% compared with that in similar foreign products. This technology has been applied to the Humen Second Bridge project.

(2) Salt crystallization inhibition technology

In a 5% Na_2SO_4 corrosive environment, the incorporation of an anti-sulfate corrosion selective crystallization inhibitor can reduce the formation of ettringite without affecting the formation of normal hydrated crystalline products such as calcium hydroxide, thereby inhibiting corrosion expansion and reducing the loss of mechanical properties of the concrete.

(3) External protective coating system for marine concrete structure

With regard to organic protective materials in an extreme environment with high salt concentration and underwater conditions, water-based and moisture-curing technologies have become an area of focus in international research in recent years. Studies have shown that epoxy and polyurethane coatings are superior to other coatings in terms of water absorption, chemical resistance, and chloride ion penetration. However, with aging, the chemical bond of the polymer is destroyed, causing the coating resin to degrade and age. The gloss of the

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coating surface is continuously reduced, along with the corrosion resistance of the coating. Currently, silicone is the most widely used permeable surface protective coating. A silicone hydrophobic film is created on the surface and the inside pores of the silicate substrate to achieve a waterproof effect. Inorganic waterproof materials have attracted extensive attention owing to their outstanding aging resistance and ecofriendly water-based properties. However, inorganic permeable protective materials need to be further improved because of the contradiction between their permeability and reactivity.

3.2.3 Long-term protection and repair technology of structural steel bars based on organic rust inhibitor

(1) Long-term rust-proof technology under alternating dry and wet phases

Using modern organic synthesis technology, multi-site strong adsorption anti-rust molecules are integrated with Cl^- transmission inhibition molecules. The rust-proof molecules are slowly released during the service of the structure, cleverly avoiding their influence on the performance of the fresh concrete. Thus, the application of high-efficiency rust inhibitor molecules in a solid structure is realized, and the rust inhibitor molecules are properly distributed. The released Cl^- transport inhibiting component builds an ion barrier in the concrete protective layer through molecular self-assembly with Ca^{2+}, ensuring the advantage of the long-term concentration of rust inhibitor molecules on the steel surface for the Cl^-.

(2) Application of nanomaterials in cement-based composites

Nanomaterials have broad application prospects in promoting the early hydration process of cement-based materials and improving their early strength. Compared with traditional early-strength agents such as calcium salts and triethanolamine, nanomaterials exhibit low sensitivity (triethanolamine and similar materials are easily retarded) and do not have harmful ions (such as chloride ions or sulfate groups), as shown in Fig. 3.

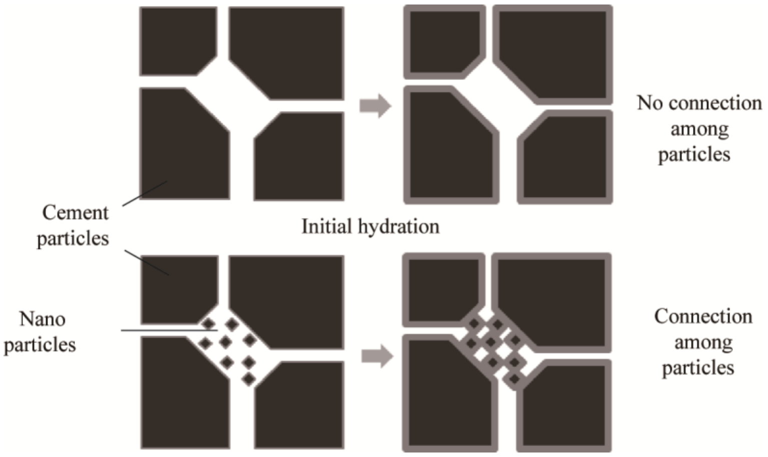

Fig. 3. Mechanism of improvement in early strength of cement-based materials using nanomaterials.

3.3 Application of FRPs in marine engineering

3.3.1 Structures strengthened using FRP

FRPs are widely applied in structural strengthening. Focusing on the problems of the aging of the adhesive in the case of applying a conventional strengthening method, a key technology of a high-permeability weather-resistant interfacial agent was proposed to improve the FRP–concrete interface of a concrete substrate. Two methods—the use of a layered anchor and stepwise tensioning—were developed, which are effective in solving the problems of a stress concentration in prestressing fiber sheets. Furthermore, an anchorage with a homogenous material was proposed to solve the problems of the stress concentration caused by an abrupt variation of the stiffness at the anchor zone of the FRP laminate/tendon. The experimental results indicated that the stiffness, cracking load, and yielding load were significantly increased by using external prestressing FRP laminates/tendons [14,15]. A complete set of tensioning and anchor technologies was developed for structures strengthened using prestressing NSM-FRP bars (Fig. 4). Additionally, the flexural and shear capacity of bridge structures can be significantly enhanced using external BFRP grids bonded with polymer cement mortar, or with FRP bars mounted into the concrete as reinforcements. Such technology has been successfully applied in the rehabilitation of the Nanjing Yangtze River Bridge in China (Fig. 5).

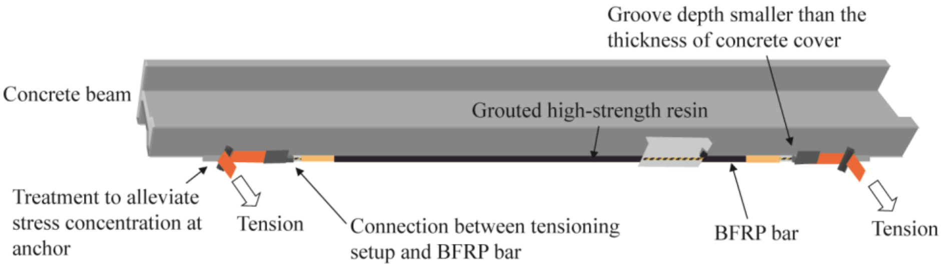

Fig. 4. Strengthening technology using NSM-FRP.

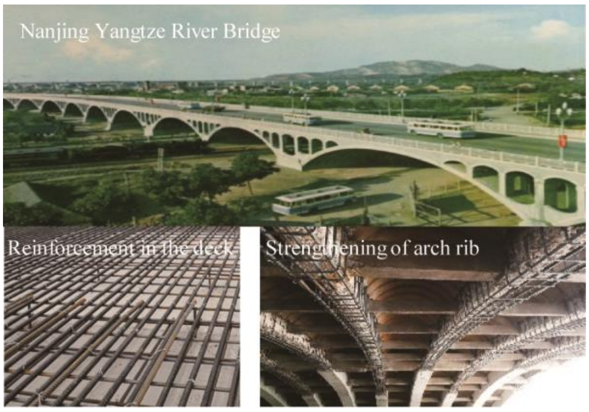

Fig. 5. Bridge deck and arch rib strengthened using BFRP grids/bars in Nanjing Yangtze River Bridge.

3.3.2 Durable and lightweight bridge deck system using FRP

An FRP–concrete composite bridge deck has superiority over a conventional concrete or FRP bridge deck. However, deficiencies in the stiffness of the FRP profile and the bond behavior between the FRP and concrete occur in this type of bridge deck. A novel prestressed BFRP–concrete composite bridge deck was developed, as shown in Fig. 6. The bond behavior between the FRP profile and the concrete is enhanced through the corrugation configuration and surface treatment on the BFRP profile. A prestress is applied to generate a camber of the BFRP profile, mitigating the deformation of the BFRP profile under the construction load. The experiment results of static and fatigue tests indicated that the loading capacity of this bridge deck reaches 644 kN [16] and that the bridge deck can withstand 2.49 million cycles at a maximum fatigue load of $0.511F_u$ and a fatigue load ratio of 0.274 [17].

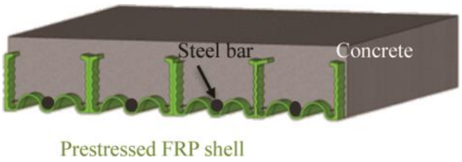

Fig. 6. Prestressed BFRP–concrete composite bridge deck.

3.3.3 Concrete structures reinforced using FRP/steel bars

Corrosion-induced cracks may occur in a cracked concrete structure. Increasing the cover thickness might further enlarge the crack width. Thus, the use of concrete structures reinforced with FRP/steel bars was proposed, with the FRP bars arranged in a concrete cover, allowing the development of cracks to be restrained (Fig. 7) owing to the stable bond behavior of the surface-treated FRP bars to the concrete [18]. Furthermore, uncontrollable damage to the RC structures due to the yielding of the steel bars is a universal phenomenon during an earthquake. Some structures are unsuitable for further service because of an excessively large deformation, despite the lack of a collapse. The proposed concrete structures reinforced with FRP/steel bars possess a stable secondary stiffness, which significantly restrains the residual deformation and enhances the resilience after a disaster [19].

3.3.4 FRP cables adopted in offshore cable-stayed and suspension bridges

According to the considerations of the mechanical properties and economic performance, the reasonable spans of various FRP cables are analyzed according to the studies on key parameters using analytical solutions. To realize an optimized design of a long-span cable stayed bridge in terms of the mechanical and economic performances, a new design for a cable-stayed bridge with a hybrid arrangement of FRP cables is proposed to take full advantage of different FRP cable materials, both mechanically and economically. Additionally, a novel FRP cable with self-damping was developed using hybrid FRP cable and a viscoelastic material to efficiently achieve a dissipation vibration energy with respect to the amplitude of the vibration (Fig. 8) [20].

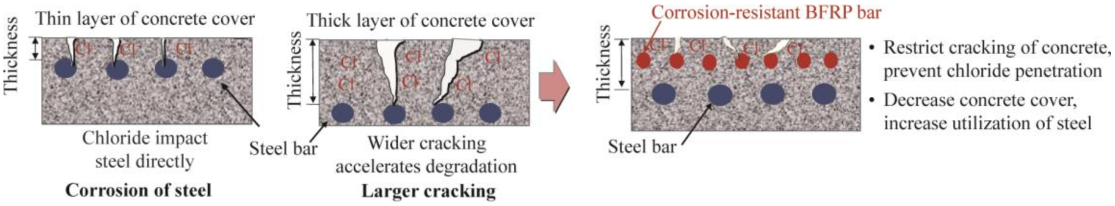

Fig. 7. Concrete structures reinforced with FRP/steel bars.

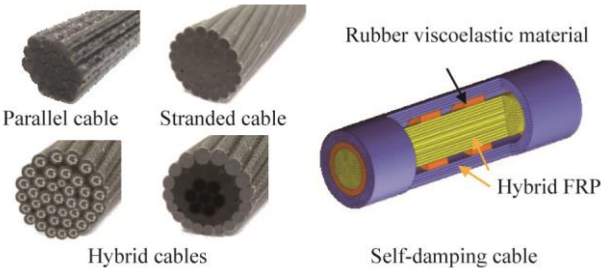

Fig. 8. Hybrid and self-damping cables.

The transverse mechanical properties of FRP are inferior to the longitudinal mechanical properties; thus, the bottleneck in applying a large-capacity FRP cable to long-span bridge structures is a proper anchor. Therefore, an integral anchor system with variable stiffness is proposed, as shown in Fig. 9. The gradient change of the radial elastic modulus of the load-transfer material is realized by setting different materials in different sections of the anchor zone. The integral solidification of an FRP cable is conducted through integral mold pressing or subsection pouring, which reduces the interface shear stress between the load-transfer material and the cable and avoids a slippage failure caused by an insufficient interface shear strength between the load transfer material and the cable [21, 22]. A series of studies indicated that the effective anchoring of a 1000-t large-capacity FRP cable can be realized using an integral homologous load transfer medium with variable stiffness. However, it is still necessary to improve the manufacturing technology of the cable-anchoring system to ensure adequate quality and reliability.

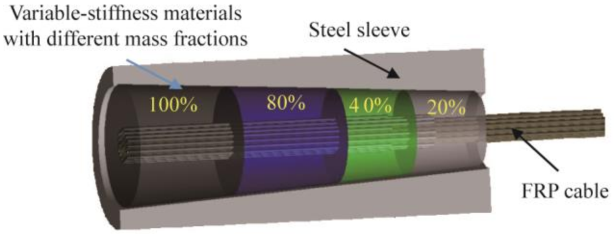

Fig. 9. Integral anchor system with variable stiffness.

4 Conclusion

In the future development of offshore long-span bridges in China, focus should be paid on the following areas. First, the corrosion mechanism and advanced key engineering materials must be studied, focusing on their ambient environments. High-performance bridge steel and ultrahigh-strength cable steel should be developed, and a standard system must be established for the engineering materials used in marine bridges. Integrated design methodologies should be proposed for the durability of the materials and structures of RC. A complete set of technologies for durability advancement based on surface protection, anti-corrosion of the matrix, and a rebar inhibitor must be developed, and relative products and standards are necessary for RC with high durability.

High-performance and corrosion-resistant FRP products should be developed for marine bridge engineering, focusing on cables, bridge decks, and anti-seismic piers. Design methodologies must be established for lightweight structures, as well as the damage-controllability, life-controllability, and durability of the structures. Furthermore, large-scale applications of lightweight materials with high strength and high durability in marine bridge engineering should be stimulated.

Additionally, with reference to the support policies for the industries of energy conservation and environmental protection, the use of nonmetallic fiber should be vigorously supported, particularly the high-performance ecofriendly basalt fiber, to enhance the longevity and sustainability of marine bridges.

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