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Technical Status, Challenges, and Solutions of Marine Bridge Engineering

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Abstract: In this study, to support the future demands, we analyzed the research developments in marine bridge engineering in China. The results indicated that strong wind waves, corrosion, high water depth, and a long span bridge scheme were some of the major technical challenges posed in marine bridge engineering today. Therefore, considerable attention should be paid to theoretical research focusing on environmental effects and their combinations, structure durability, fatigue resistance, and lifetime design. Moreover, major efforts should be made to overcome key technical impedances, such as schemes to harness super-large span bridges, ultra deep water infrastructures, and new structural forms that can be rapidly constructed. We propose an initiative in the form of a national research center for the study of marine bridge engineering technologies. Additionally, we suggest reinforcing investments toward science and technology hardware, to nurture innovative talents, and improve the science and technology reward mechanism.

Keywords: marine bridge engineering; design theory; structural form; key challenges; technical development direction

1 State-of-the-art structures in marine bridge engineering

Bridges have consistently served as key transportation infrastructural facilities. In particular, marine bridges are critical for promotion of ocean power and transportation power strategies, as well as the Belt and Road Initiative and social economy [1,2]. In the past 20 years, China has made great technological advances in the construction of marine bridges and has built a number of long span bridges across its major seas. The construction of bridges in China initiated inland and has since expanded toward the offshore areas. The Donghai, Hangzhou Bay, Hong Kong–Zhuhai–Macao, and other cross-sea bridges have been built progressively in the past few years. The last of them is the Pingtan Strait Bridge, which is currently under construction. The construction technology of offshore bridges has made remarkable progress [3]. The promotion of the ocean power strategy and the Belt and Road Initiative has resulted in the construction of additional marine bridges over the Qiongzhou Strait, Bohai Bay, and Taiwan Strait. Meanwhile, countries along the Belt and Road are planning to build a few deep water bridges, such as those crossing the Sunda Strait (in Indonesia) and Caspian Sea (between Russia and Iran).

1.1 China’s technological achievements in marine bridge engineering

1.1.1 Development of large scale prefabrication technique, transporting/hoisting technique, and related equipment

The non-navigable spans of the Donghai and Hangzhou Bay bridges are made of prestressed concrete box girders 50 m and 70 m respectively in length, while those of the Hong Kong–Zhuhai–Macao Bridge incorporate steel box and steel concrete composite girders that stretch for as long as 110 m and 85 m, respectively. A

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prefabricating technique was applied in the construction of the piers and pile caps of the Hong Kong–Zhuhai–Macao Bridge. Welded joints, and a construction technique for the full span erection of steel truss girders, were used in the construction of the Pingtan Strait Bridge. The components of this bridge were integrally prefabricated in the factory before their transportation, erection, and installation at the selected location. “Cygnet” and “Tianyi” cranes (having deadweight tonnages of 2500 t–3000 t), a floating crane (lifting weight of 3600 t), and a trolley (capable of erecting a full span precast beam on the girders) were all manufactured accordingly.

1.1.2 Improvement in durability

High-performance concrete and its associated crack prevention technique, the cathodic protection of steel pipe piles, heavy duty anti-corrosive coating, and durable spherical cast steel bearings have been widely used in bridge engineering. The Donghai Bridge resists fatigue cracking by employing concrete slabs instead of a steel deck; moreover, a cable-stayed bridge, with 420 m long steel box composite beams, crosses the main channel. Meanwhile, precast and prestressed concrete trough beams are used as the railway deck of steel truss beams in the Pingtan Strait Bridge.

1.1.3 Application of GPS kinematic positioning techniques to construction at sea

Cross-sea bridge engineering employs a GPS reference station system that can work continuously to meet the precision requirements of the plane (3 cm–5 cm) and height (5 cm–10 cm) positioning in real time. This system can be useful for the construction of steel pipe piles and steel casings at sea. Moreover, an independent coordinate system has been developed to avoid projection errors and ensure the accuracy of construction lofting.

1.1.4 Application of large scale wind barriers

The Pingtan Strait Bridge employs large scale wind barriers, consisting of porous metal strips on both sides of the railway and highway decks, ensuring ventilation rates of 50% and 36.5%, respectively.

1.1.5 Application of rapid and efficient maintenance

The Hong Kong–Zhuhai–Macao Bridge is equipped with an electric inspection vehicle within and at the bottom of the main girders; moreover, a fast inspection passage is located at the bottom of the main girders. These elements reflect its visible, accessible, repairable, and replaceable design.

1.1.6 Development of construction technologies and equipment for large diameter steel pipes and bored piles

The Hangzhou Bay Bridge harbors steel pipe piles having diameters of 1.5 m and 1.6 m and lengths of 71 m–89 m. The most advanced multifunctional pile driving vessels, equipped with a full circle crane, were used for its construction. These vessels were equipped with type S-280 dual function hydraulic hammers. The Pingtan Strait Bridge is the first to adopt a one-piece bored pile with a diameter of 4.5 m. Moreover, a type KTY5000 drilling rig, with a multiblock combined drill, has been developed for its construction.

1.2 Shortcomings of current technologies employed in marine bridge engineering

In the past 20 years, the technologies employed in the construction of marine bridges have made great progress; however, they still present several shortcomings. While aiming for “learning and catching up” in the 1980s and “improving” in the 1990s, Chinese researchers studied and introduced new materials, technologies, as well as the arts and crafts created by foreigners during the construction climax that followed World War Ⅱ. Although some progress has been achieved locally through practice, original scientific and technological findings have been scarce in China [4].

Current national codes for marine bridges are underdeveloped when compared to those employed in Europe and U.S.A., in terms of design, construction, maintenance, and reinforcement. Many Chinese codes refer directly to existing foreign codes, without considering the latest (national and international) scientific and technological achievements in design and construction. Presently, there is no code dedicated to marine bridge engineering in China. Although this branch of engineering has made great progress in China, at least for what concerns the construction scale, meaningful improvements and scientific/technological achievements have been limited.

2 Technical challenges in marine bridge engineering

With the promotion of the national ocean power strategy and the Belt and Road Initiative, the application of marine bridge engineering in China has burgeoned from offshore to deep water areas, generating new needs and challenges. The new environmental and construction challenges faced by cross-sea bridge engineering in the deep

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water areas can be grouped under four main aspects, viz., (1) Complex environmental effects (e.g., strong winds, high waves and torrents, violent earthquakes, tsunamis, etc.), which are often extreme, random, and closely coupled, (2) A particularly early, quick, and serious deterioration of structural performance, accompanied by a decrease in durability, due to the exposure to corrosive environmental conditions (e.g., high temperatures and humidity, salt corrosion, freeze-thaw cycles, and sea fog) over long time spans, (3) Water depths (usually > 100 m) and particularly complex hydro-geological conditions [5], and (4) The necessity to satisfy the requirements of bi-purposed bridges, continual traffic notwithstanding weather conditions, and high speed railway transportation over large bridge spans (> 2000 m). The construction of cross-sea bridges is constantly subject to harsh environmental conditions (e.g., deep waters and torrents, high wave), and environmental loads (e.g., strong winds, earthquake forces, erosion, wave forces), which are altogether different from those of inland bridges. Therefore, current theories and bridge/structure designs are hardly able to satisfy the standards required by marine bridge engineering [6]. The key technical challenges faced during the construction of these bridges are summarized by the five aspects presented in the following subsections.

2.1 Lack of code regarding single and combined environmental effects on marine bridges

The calculation theory of the load effect and the loading combinations are on the basis of the design of the marine bridges. It is an important premise to satisfy the design principles of “safety, durability, applicability, economization, and aesthetics.” Owing to advancements in the branch of elastic-plastic fracture mechanics, the design theory of bridge engineering has changed: the limit state method has recently replaced the traditional allowable stress method. Moreover, the application of the limit state method, based on the reliability theory, has facilitated the development of design of bridge engineering. The design (previously based on the fixed value and half probability methods) is now based on the approximate probability method.

Presently, the wave forces, that the marine bridges should be able to sustain, are calculated in accordance with the design codes for port engineering among other codes. However, port and marine bridge engineering are different from each other in that marine bridges are primarily offshore structures and considerably larger than those of the ports, which are located along the coast. Ocean environmental loads are characterized by significant intensity, changes, randomness, and strong coupling. For example, typhoons, torrents, and huge waves often occur simultaneously in the ocean, while earthquakes are often accompanied by tsunamis. Therefore, it is necessary to undertake a large number of theoretical and experimental studies to calculate the wave force and load factors of multifield coupling (air and sea coupling, earthquake and tsunami coupling, and so on) on marine bridges. The corresponding research results can then be utilized to prepare codes that align better with the characteristics of marine bridge engineering, and explore the correlations between wave forces and water depth, structural dimensions, meteorological conditions, and ocean currents. Presently, however, such studies can be based on only a few engineering samples.

2.2 Quantitative design of the structural durability required in marine bridge engineering

“Structural durability” defines the ability of structures to maintain their long term performances against atmospheric influences, chemical erosion, and other deteriorative processes. The durability of marine bridges is one of the most complex design issues. In fact, it considers not only the long term security and durability of the structure, but also the resources needed, environmental conditions, national economy, people’s livelihood, etc. Research on structural durability are of practical significance to public security, besides supporting resource saving and a sustainable development.

The main building materials used in marine bridge engineering are concrete and steel. In environments characterized by high salinity, humidity, and temperatures, the durability of both concrete and steel structures tends to be severely compromised. Concrete structures are easily degraded in the ocean due to the carbonization of concrete, chloride ion penetration, and corrosion of steel bars. Changes in properties and various functional damages are caused by chemical interactions between the steel structures and chloride ions present in the highly saline marine environment. Presently, the relationship between performance and lifetime, in the context of durability design, is still not clear. The design concept and the quantitative design method based on performance have both not been completely established yet, and the technical standards for different industries vary in this regard. In particular, it is necessary to understand the damage mechanism for concrete structures: establish a resistance degradation and prediction model, learn how to detect and evaluate damages, apply a heavy duty anti-corrosive coating on steel structures, detect and monitor their corrosion, establish lifetime anti-corrosion designs, and fabricate an efficient anti-corrosion steel.

2.3 Coupling effects of structural fatigue on marine bridges

Permanent structural fatigue cracking is caused by local damages under repeated loads (which are far below the yield strength under a static load). The traffic loads sustained by highways (or railways) on marine bridges are usually compared to those related to ocean shipping; moreover, inland and marine bridges present significantly different load characteristics. Marine bridges exhibit fatigue problems generated not only by vehicle operation (similar to inland bridges), but also by variable ocean winds and currents, which can create extreme conditions. At present, there still exist technical challenges in the classification of fatigue and definition of the fatigue load spectrum: these are fundamental to the establishment of effective fatigue resistance designs in bridge engineering. Some of the technical difficulties that need to be overcome are the estimation of fatigue life, fatigue load spectrum, coupling effects in the cross-sea traffic ways, and interactions between fatigue and corrosion.

2.4 Lifetime designs for marine bridges

Similar to other construction engineering domains, the lifetime design, i.e., optimization design of the overall performance (function, cost, humanity, environment, etc.), of bridge engineering includes planning, construction, operation, maintenance, demolition, recycling, and reusing. The concept of lifetime design has been developed only in recent years; hence, it is far from perfect. This is especially true in the context of marine bridge engineering, where several technical challenges, such as the establishment of a calculation model, a standard for the life-time costs, a risk assessment system, and practical methods, need tackling.

2.5 Bridge type/structure availability in marine bridge engineering

Marine bridge engineering needs to consider an array of complex conditions, such as the location of the structures in offshore deep waters and a harsh natural environment (e.g., strong winds, high waves, torrents, high salinity, humidity, and temperatures). Therefore, it is necessary to investigate specific bridge types and structures adapted to the ocean environment.

Cable-stayed, suspension, and cable-stayed suspension configurations are common in the construction of super large span bridges. In addition, multi-pylon cable supported configurations are advantageous (technically and economically) for the construction of long span cross-sea bridges in deep waters, since they allow the creation of multiple continuous large spans, which facilitate navigation, and reduce the impact on the ocean environment. Presently, there are only three long span three-pylon suspension bridges in the world, all built in China over the Yangtze River. The main spans of the Taizhou and Maanshan bridges have dimensions of 2 × 1080 m, while the two main spans of the Yingwuzhou Bridge cover an area of 2 × 850 m. Several multi-pylon cable-stayed bridges have been built in China and abroad, with their largest span exceeding 600 m. More research needs to be undertaken before the multi-pylon cable supported configuration can be applied in marine bridge engineering, in addition to addressing technical encumbrances, such as understanding how to improve the bridge span, increase the number of continuous spans, and augment bridge stiffness and resistance to the sliding of the main cables. Concurrently, materials of superior quality, as well as disaster prevention and reduction, structural, construction control, health monitoring, lifetime management, and maintenance systems need to be developed.

Presently, known types of deep water foundations include large diameter piles, pipe piles, and large open caissons; moreover, large equipment is needed for the embedding of foundations and underwater construction. For rapid constructions, large segments of precast structures for the main beams, main steel pylons, and bridge substructures are employed. It is, nevertheless, necessary to overcome key technical challenges, such as the creation of new structural forms, high-performance materials, and intelligent testing equipment, as well as the construction of deep water foundations, and development of large scale automated construction.

3 Policy recommendations for the development of marine bridge engineering technologies

3.1 Consolidation of scientific research investments

We propose an initiative to establish a national scientific research center or technology innovation base for marine bridge engineering, capable of heading new investigations whilst also collaborating with other research institutes. Additionally, we aim to integrate the resources of industrial (national and provincial) laboratories to

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facilitate niche research, rescind low-level studies, and improve the efficiency, benefits, and quality of innovation. Therefore, the following types of research work are proposed: (1) systematic research on lifetime planning, anti-disaster design, industrial construction, and intelligent management and maintenance of marine bridges; (2) establishment of national scientific and technological projects in marine bridge engineering; (3) scientific studies in marine bridge engineering undertaken for specific sites (for the Qiongzhou Strait, the Taiwan Strait, etc.), which can help to bolster the technical reserves needed for the implementation of the ocean power and transportation power strategies, and the Belt and Road Initiative; (4) renovation of the current system used to access marine information; establishment of joint observation systems to monitor meteorological conditions, sea conditions, and engineering requirements in specific sea areas; and creation of a platform for data sharing (which would expand sci-tech research).

3.2 Improvement of the scientific research system

During the project approval process, the government and competent industrial authorities should guide relevant enterprises to dispense significant investments toward continuous research in science and technology; endorse new technologies, materials, and techniques, and be cognizant of the novel scientific and technological innovations. Moreover, it is recommended to establish a technology innovation system that focuses on enterprises, meets the market needs, and complements the production, education, and research aspects.

3.3 Improvement of talent training and scientific/technological reward mechanisms

Special majors should be introduced in select universities to cultivate compound talents, in addition to fostering appropriate academic exchanges; moreover, a sustainable development of marine bridge engineering should be promoted. Multiple strategies (e.g., organizing big awards, science and technology shares, and commissions for technology transfers) should be adopted to encourage technological innovation and the application of research results to production. Meanwhile, incentive funds should be established in the context of market economy to reward the personnel who make outstanding contributions to the industrial technological progress. All these strategies should be included in the national innovation mechanism.

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