The Yushan Bridge located in the Zhoushan Islands of Eastern China’s Zhejiang Province, is a long sea-crossing bridge built with accelerated bridge construction technology. It is recognized as a milestone bridge project in China utilizing the new generation of industrialized construction technology. The bridge is 8km in total length and has a main bridge section that consists of a continuous rigid-framed concrete box girder superstructure arranged in 70m+140m+180m+260m+180m+140m+70m, totaled 1040m. The 260m hybrid main span uses an 89m-long steel box-girder section at the mid-span to reduce potential long-term sagging. The approach bridge section adopts the continuous concrete box girder superstructure with span length of 70m and 50m.

The Zhoushan Island served as a sea gateway and access for opening up of the Yangze River Basin and Yangze River Delta. It embraces the Ningbo-Zhoushan Port and the Shanghai Port, respectively the busiest ports with the largest cargo handling capacity and the largest container port in the world. The sea-crossing projects are planned for linking Shanghai, Zhoushan and Ningbo to facilitate the national strategic plan of regional economic integration in the Yangze River Delta. As the first step in the plan, Yushan Bridge needs to be completed within 27 months. However, the bridge is isolated in the open sea suffering from frequent typhoons and monsoons, with the design standard wind speed of 44.35m/s and the tidal velocity of 3.69m/s, limiting the annual effective working time to only 8 months. Besides, the sludge on the seabed reaches 40m, and the bedrock fluctuates heavily with local depth over 140m. Therefore, it poses a great challenge to us to build an 8km-long sea-crossing bridge within 27 months under such complicated and vile marine construction conditions.

All-trestle construction and large-diameter single-pile-single-column engineering schemes are adopted for the substructure of the 7km-long approach bridge, the most difficult part of the project. The 8km-long trestle was completed in only 3 months by applying modular design and quick assembling, thus solving the transportation and operation problems of construction equipment, personnel and materials. The single pile foundation, with a maximum diameter of 5m and a maximum length of 148m, can reduce construction time, wave force, scouring depth and cost respectively by 40%, 80%, 20% and 30%, it can also reduce the exposed area in sea by 75% which greatly enhances the durability. Besides, a whole set of construction technology is proposed creatively to solve the construction problems including difficult positioning at sea, large tonnage of reinforcement skeleton and large volume of concrete in pile foundation. The integral hoisting time for the complex reinforcement skeleton of pier body was shortened to 4 hours on site through modular binding. As a result, all pier bodies and pile foundations are tested to be of fine quality, with inclination less than 1/220, and construction time was reduced to 15 months from scheduled 20 months.

The superstructure of the whole bridge adopts the industrialized construction technology incorporating standardized design, industrialized segment prefabrication and erection on site from multiple working faces simultaneously. As a result, rapid and environment-friendly construction is achieved through parallel operations of both superstructure and substructure, while construction time has been greatly reduced. By applying advanced technologies such as Internet of Things, welding robot and real-time big data monitoring. A total of 2370 girder segments were prefabricated within 15 months averaging 1 in every 3 days, and 7 main girders were erected per day with the installation of all prefabricated girder sections completed within 14 months. Millimeter precision was achieved for both prefabrication and installation.

Bridge-erection machine with high wind-resistance capacity was developed and synchronous incremental launching system was deployed to adapt to vile construction environment. When moving from one span to erect another, it only caused 2mm displacement of pier top, thus ensuring construction safety. Moreover, a structure consisting of prefabricated shell and cast-in-situ core was invented for the closure section on pier top, and the concrete with ultra-high toughness is applied to the deck pavement of steel box girder. Through collaboration with universities and research institutions, a number of engineering design and construction techniques have made new records. Three techniques have won awards, and over ten achievements are under evaluation for awards.

The project has drawn wide attention among industrial peers. So far, 160 delegations and over 1000 technicians have visited the engineering site, while the project site has become a key practical teaching base for several universities. Besides, with the engineering reputation of the project, the 2018 International Symposium on Key Technologies for Industrialized Construction and Accelerated Bridge Construction (ABC) was successfully held, which has facilitated the first collaboration between American Accelerated Bridge Construction Technology Expert Group (ABCTEG) and China.

After its completion, the Yushan Bridge will become a landmark in the Daishan Island. With its duly designed horizontal curve and harmoniously arranged span, the whole bridge draws up a beautifully S-shaped curve over the sea. The bridge has met the requirements of navigation and planning and relieved its impact on marine ecology. Through innovative design, construction methods and IT-driven industrialized construction model, an 8km (5 mile)-long sea-crossing bridge of outstanding design and engineering was built within 27 months and with a total investment of only 310 Million USD. The Yushan Bridge has created a miracle in bridge engineering by achieving a proper balance between construction period, quality and cost. This project is eminently worthy of the IBC Gustav Lindenthal Medal. Recognition by the IBC would be a great honor and undoubtable encouragement to all who have devoted their time and effort to the bridge.
Detailed Description of Yushan Bridge

1. Introduction

The Yushan Bridge, located in the Zhoushan Islands of Eastern China's Zhejiang Province, provides the only land connectivity between Yushan Island and Daishan Island (the second largest island in Zhoushan Islands).

The total length of the bridge is 8.815km including 7.8km offshore bridge. The Main Bridge is a continuous rigid framed of steel-concrete hybrid structure with a total length of 1040m (70m+140m+180m+260m+180m+140m+70m), the longest continuous bridge frame in the world. The superstructure of Main Bridge is built of precast concrete box girder segments with an 89m prefabricated steel box girder segment in the mid-span of 260m span. The approach bridge consists of continuous box girders frames of 70m-span in deep water and 50m-span in shallow water.

The superstructure of entire bridge was constructed of precast concrete box girder segments, except steel section in the mid-span of main span. The substructure of approaches use a large-diameter mono-pile and pile shaft design and was built by the means of a full length trestle. The application of new-generation industrialized accelerated construction technology enabled this 8km sea-crossing bridge to be completed with high quality within 27 months under difficult and complicated marine environment conditions. Through collaboration with universities and research institutions, a number of engineering design and construction techniques have made world records: the main bridge is the first steel-concrete hybrid girder bridge using segmental erection in the world; its 1040m couple length and 260m main span length are the greatest among precast segmental-erection concrete girder bridges in the world; its 12.14m high segments are the highest concrete segments in the world; the single pile with a maximum diameter of 5m for its approaches is the largest-diameter steel-tube composite pile in the world and the largest-diameter cast-in-place bored pile at sea. In addition, it is the first sea-crossing bridge using all-trestle construction technique in China.

Comprehensive and intensive study into accelerated construction technologies carried out for Yushan Bridge opened a new horizon for development of accelerated bridge construction technology, with outstanding achievements made in technical innovation, aesthetic merits, environmental harmony and community participation. These remarkable achievements make it worthy for the Gustav Lindenthal Medal.

2. Technical Challenges to the Project

2.1 Urgent Need for Construction

Zhoushan is a sea gateway and access for opening up of the Yangtze River Basin and Delta, home to Zhoushan Port, the busiest one with the largest cargo handling capacity in the world, and Shanghai Port, the largest container port in the world. In order to implement the national strategy of integrating regional economies in the Yangtze River Delta, a sea-crossing project was planned to link Shanghai, Zhoushan and Ningbo. There was an urgent need to complete Yushan Bridge, one of the pilot works for the project, within 27 months.

2.2 Harsh Climatic Conditions

However, Yushan Island has been isolated in open sea since ancient times, with up to 6 average annual typhoons, up to 173 days of average annual monsoon season, up to grade-11 monsoon intensity, design reference wind speed of 44.35m/s and maximum tidal velocity of 3.69m/s. Conventional construction methods would have been able to provide less than 200 days of effective operation time at sea.

2.3 Complicated Construction Environment

The sea bed is covered with 20-40m thick sludge. The fluctuating bedrock is more than 100m deep and deeper than 140m locally. Submarine cable lines are densely distributed at the site of main bridge.

In such complicated and harsh marine environment, it was a huge engineering challenge to rapidly complete this 8km sea-crossing bridge within 27 months. With consideration given to structural performance, construction capacity, economic rationality and environmental harmony, accelerated green construction technologies based on a new-generation industrialized construction concept were adopted, on the principle of minimizing working procedures, time and personnel for operation at sea.
3. Innovative Accelerated Construction Technologies

3.1 Substructure

The greatest difficulty was how to complete the substructure of 7km approaches within a very limited time frame. The engineers addressed this problem using all-trestle construction technique and large-diameter single-pile-single-column engineering solution.

3.1.1 All-Trestle Construction Technique

All-trestle construction technique was proposed to solve the problem of transporting construction equipment, personnel and material in harsh marine environment. A 7.8km-long continuous trestle using modular design and assembly technique was first built along the bridge axis within 3 months to turn operation at sea into operation on quasi-land, thereby increasing annual effective operation time at sea by nearly 100 days. Meanwhile, a 2×64m precast steel truss trestle was erected at the main span of the navigable bridge to facilitate crossing complex submarine cable lines.

3.1.2 Large-Diameter Single-Pile and Pile Shaft Engineering Solution

The single-pile and pile shaft structure without pile cap is adopted in design of the substructure and foundation for the approaches. The single pile is a steel tube composite pile with large diameter and length, up to 5m and 148m respectively. In comparison with group pile foundation (4 piles) with the same capacity, this solution reduces construction time by 40%, water blockage by 80%, scouring depth by 20%, construction cost by about 30%. It can also reduce the exposed area in sea by 75% which greatly enhances the durability. To address construction difficulties for super long and large pile foundation such as positioning at sea, large diameter, high tonnage of reinforcement skeleton and large volumes of concrete, a complete set of innovative construction techniques was proposed: Driving 5m-diameter 65m-long steel pipes using pile driving barge and the application of sinking guide and T-type measurement method solved the problem of accurately positioning super long and large steel pipes at sea, limiting pile offset to within 3cm; the application of ZJD5000/450 hydraulic whirling drill with a high power of 355kw and capability to drill 5.0m-diameter, 200m-deep piles, over-sized rod stabilizer, overweight drill bit counter weight accessory and decompressed slow drilling technology solved the problem of drilling deviation for super large and deep hole due to uneven geological hardness at the same level; a reinforcement skeleton installation technique of lifting individual segments for positioning with crawler crane and then carrying and placing the whole section with floating crane was proposed to ensure docking quality and work efficiency of 148m long, 241t reinforcement skeleton under harsh marine conditions; the large-volume concrete delivery technique based on continuous trestle enabled successful pouring of 2000m³ underwater concrete within 12h so that the piling quality was assured.

The pier column, due to its hyperboloid vase-shaped structure, requires complex reinforcement skeleton and is difficult to bind. It was made modularly in the factory using long line method and then delivered to site for integral erection which took only 0.5 days, compared to 15 days required for common shaping process on site. This not only significantly reduced overall construction period but assured the quality of member fabrication. Each pier body and pile foundation is of high quality, with inclination less than 1/220. Overall construction period was reduced by 5 months, to only 15 months.

3.2 Superstructure

The superstructure of the whole bridge was designed and built with standardized segments precast in the factory and erected on site from multiple working faces simultaneously. The superstructure was constructed in parallel with the substructure, significantly reducing overall construction period.

Internet of Things, welding robot, real-time big data monitoring and other advanced technologies were applied during construction, effectively improving member fabrication quality and efficiency. Precasting 1 girder segment only took 3 days and 2370 girder segments were precast in 15 months. The main bridge with super long span was erected using bridge deck crane; the approaches with span of 50m and 70m were erected using segment-by-hole assembly with launching girder and cantilever erection technique. To adapt to the harsh construction environment, an offshore launching girder with high wind resistance was developed and provided with a synchronous incremental launching system. When moving from one span to erect another, it only caused 2mm displacement of pier top, thus assuring construction safety. A continuous pier top block with precast shell and cast-in-place core was invented for 50m box girder, overcoming the difficulties of long construction time and cracks with cast-in-place
section on pier top. On average, 7 girder segments were assembled per day, and precast girder segments were installed within 14 months. Millimeter precision was achieved for both precasting and installation. Precasting precision of box girder segments was limited to 4mm; the 89m steel box girder at mid-span of the main bridge was erected with a closing axis deviation of 8mm only and elevation difference of only 7mm.

4. Material Innovation
To increase the fatigue strength of steel box girder and the service life of pavement, the steel box girder deck is constructed of high-ductility concrete with ultimate tensile strain of 2%, which can fully adapt to the deformation of steel; a new type of long-lasting epoxy-coated steel strand is used in concrete box girder as external tendon.

5. Aesthetic Merits
Upon its completion, the Yushan Bridge will become a landmark of Daishan and a representative landscape juxtaposed with the traditional “Ten Views of Penglai” in Daishan. Designed in reasonable horizontal curve, the bridge looks as if it is a graceful S-shaped curve drawn over the sea; and as its name —Yushan (fish mountain)—implies, it is also like a big fish swimming in the vast sea. The longitudinal section of the whole bridge has harmonious and beautiful curves. With rational design of navigable bridge and connecting slope points on both sides, it is just like a sketch of mountains and sea connected. Spans of the navigable bridge are well-proportioned in approximation to golden section, making the bridge couple toughness with softness. The perfect combination of the soft curve and majestic structure of Yushan Bridge represents the indomitable and enterprising spirit of Zhoushan people, the great prospect of the Ningbo-Zhoushan Port as the world's largest port, and the beautiful vision of Zhoushan as the bridgehead of the Belt and Road.

6. Harmony with the Environment
The Yushan Bridge built on an industrialized basis has little impact on environment as the accelerated construction technology has effectively reduced the pollution of marine environment from offshore operation; impact of construction on environment is minimized by taking a series of environmental protection measures during project construction. For example, dust-arrester installation is provided at the mixing station in factory for fabrication to avoid dust pollution; automatic spraying circulating water supply system is adopted in curing of prefabricated members to avoid waste of water resources in island cities; diesel generators are replaced by commercial power during operation at sea to effectively reduce carbon emission and air pollution; PHP environment-friendly mud is used in construction of pile foundation; boring mud is transported rapidly by continuous trestle and discharged at designated place. During construction, full-process strict environmental monitoring has been implemented and no environmental pollution problem has occurred.

7. Community Participation
In the course of design and construction, the Employer, the Designer, and the Contractor conducted intensive studies on the project in collaboration with Tongji University, Hong Kong University of Science and Technology, Zhejiang University, Hehai University, and other scientific research institutions. Successful implementation of the project has attracted broad attention from domestic and overseas counterparts. So far, 160 delegations and over 1000 technicians have visited the engineering site, while the project site has become a key practical teaching base for several universities in China such as Tongji University and Zhejiang University. Besides, with the engineering reputation of the project, the 2018 International Symposium on Key Technologies for Industrialized Construction and Accelerated Bridge Construction (ABC) was successfully held, which has facilitated the first collaboration between American Accelerated Bridge Construction Technology Expert Group (ABCTEG) and China.

8. Significance of the Project
Successful application of industrialized and accelerated construction technologies to the Yushan Bridge has enriched the design theory and construction methods of accelerated sea-crossing bridge construction technology and is a model of modern bridge industrialization. This not only provides strong protection for marine environment, but also promotes the construction of the sea-crossing project connecting Shanghai, Zhoushan, and Ningbo as well as the economic integration development of the Yangtze River Delta Region represented by the Ningbo-Zhoushan Port and the Shanghai Port,
highlighting the strategic position of Zhoushan as the bridgehead of China's Belt and Road Initiative. Comprehensive research and exploration have been conducted in the accelerated construction of sea-spanning bridge, and pioneering, innovative outcomes have been obtained. This project has opened up a new world for development of accelerated bridge construction technology. It embodies the courage of engineers in innovation and pursuit of excellence, cultivating bridge engineers who have a pioneering and innovative spirit. It has also injected fresh blood in the bridge industry, and set a new benchmark for subsequent projects. The Yushan Bridge Project is a recent outstanding achievement in technical and material innovation, aesthetic merits, harmony with the environment, and community participation. This project is eminently worthy of the IBC Gustav Lindenthal Medal. Recognition by the IBC would be a great honor and undoubtable encouragement to all who have devoted their time and effort to the bridge.