The Zhoushan Mainland-Island Linking Project Consisting of Five Sea-Crossing Bridges

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Abstract: This paper introduces the construction and provides general information on the Zhoushan Mainland-Island Linking Project, which includes five sea-crossing bridges. The primary focus is on the Xihoumen Bridge and the Jintang Bridge.

Key words: Zhoushan; mainland; mainland-island linking project; sea-crossing bridge.

Situated at the eastern part of the Yangtze River Delta, Zhoushan is a famous sea port, fishing port, and tourist city. It is referred to as "the Pearl in East China Sea". It contains more than 1300 islands within in its jurisdiction area. Although the straits separting Zhoushan from the mainland are beautiful, they pose a barrier to the transportation between the mainland and islands. The Zhoushan Mainland-Island Linking Project was launched in the 1990s to enhance the development of the Zhoushan Prefecture. Expected to be completed in 2009, the project will link the mainland to the five islands, providing convenient transportation for the local people. (Fig.1)

Fig.1 Alignment of Zhoushan Mainland-Island Linking Project

1 Construction Scale

The project begins at the round-the-island highway at Yadan Mountain, links with the National Road 329 and the outer ring road of Dinghai City, passes through Lidiao Island, Fuchi Island, Cezi Island, Jintang Island to Ningbo Zhenhai, connects with Ningbo Ring Road, and overpasses Cengang Waterway, Xiangjiaomen Waterway, Taoyaomen Waterway, Xihoumen Waterway, Ligang Waterway and Huibieyang Sea. In short, the project crosses five islands and six waterways for a total length of 49.96 km. The five large sea-crossing bridges of the project are introduced in this paper.

2 Main Technical Criteria

The main technical criteria are as follows:

(1) Highway grade: dual-way four-lane expressway
(2) Design speed: 60 km/h for the first phase; 80 km/h and 100 km/h for the second phase
(3) Vehicle load grade: car-super 20, trailer-120; car-Class I
(4) Route width: bridge width 22.5m for the first phase, 23.5m/26m for the second phase
(5) Seismic intensity: Degree VI for the Cengang Bridge, the Xiangjiaomen Bridge and the Taoyaomen Bridge, Degree VII for the Xihoumen Bridge and the Jintang Bridge
(6) Navigational clearance: see Table 1.

Navigational Clearance for Each Bridge

Table 1

Name of bridge	Name of navigational span	Typical vessel	Type of channel	Navigational clearance（m）	
				Net width	Net height
Cengang Bridge	East &west navigational span	300 t seagoing ship	Single way	40	17.5
Xiangjiaomen Bridge	Main span	500 t seagoing ship	Double way	130	21
Taoyaomen Bridge	Main span	3000 t cargo ship 3000t warship	Double way Double way	340	32
Xihoumen Bridge	Main span	30000t seagoing ship reconnaissance ship	Double way Double way	630 <630	44 49.5

Jintang Bridge	Main span of main navigational span	50000t bulk cargo carrier	Double way	544	44
	Side span of main navigational span	1000t seagoing ship	Single way	109	25.5
	East navigational span	3000t oil tanker	Single way	1211	28.5
	West navigational span	500t general cargo vessel	Double way	126	17

3 Completed Bridges

The first phase project, which includes three sea-crossing bridges (the Cengang Bridge, the Xiangjiaomen Bridge, and the Taoyaomen Bridge) has been completed.
The Cengang Bridge is 220 m in length and includes three main spans of 50 m, which are prestressed concrete parallel T-shaped girders. The Xiangjiaomen Bridge is 810 m in length and includes main spans of 80+150+80 m, which are continuous prestressed concrete box girders.


Fig.2 Cengang Bridge


Fig.3 Xiangjiaomen Bridge

The Taoyaomen Bridge, the most exceptional bridge of this set, is a double-pylon double-cable-plane seven-span continuous hybrid cable stayed bridge with a main span of 580 m and a total length of 888 m. (Fig.4 and Fig.5)


Fig.4 Taoyaomen Bridge

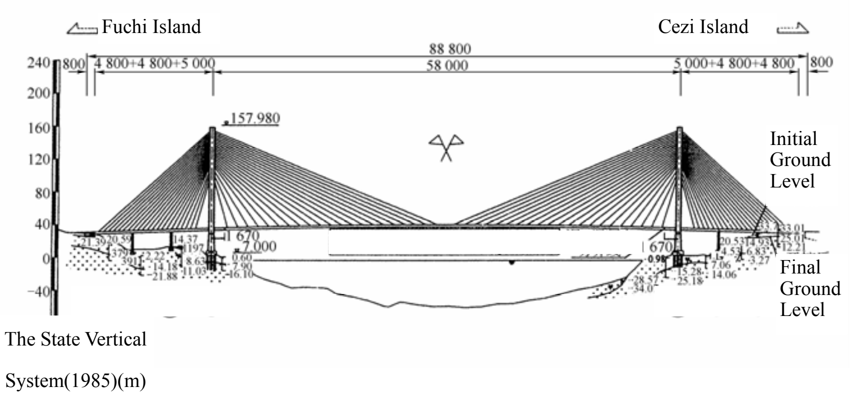

Fig.5 Arrangement of Taoyaomen Bridge

The main bridge has three primary characteristics:

(1) In order to fit in with the topography and avoid a large amount of excavation, the ratio of side span to main span is 0.25. To maximize dead load of the side spans, they are built as prestressed concrete box girders with concrete blocks added to the interior cavity of the box.

(2) The joint between the concrete and steel girders is made at a location with zero bending moment due to dead load, thus ensuring that compressive stress across the joint will be evenly distributed.

(3) The steel-concrete composite segmental structure, the cross section of steel box girder at central-span, cable anchorage details, and type of wind fairing have all been optimized and innovated.

4 Xihoumen Bridge

The Xihoumen Bridge, the fourth sea-crossing bridge of the project, links Cezi Island to Jintang Island. This bridge is a two-span continuous steel box girder suspension bridge. Its 1650 m main span ranks first among steel box girder suspension bridges in the world. The spans of bridge are arranged as 578 m + 1650 m + 485 m. The span to sag ratio of the main cable is 10:1. A steel box girder suspended structure is used for the north side span and the main span. Two 6x60 m prestressed concrete continuous box girders are used for the southern side spans. The foundations for the pylon are not set in water, thus avoiding the construction of deep-water foundations, ship collision, and corrosion by sea water.

Fig.6 Xihoumen Bridge

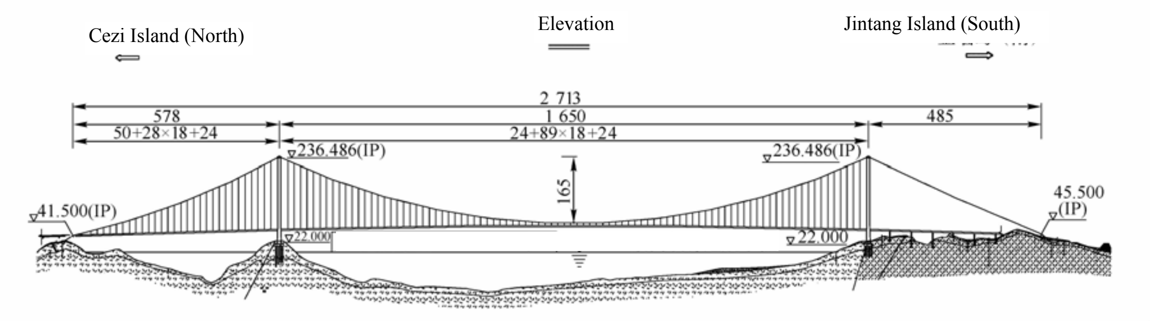

Fig.7　Arrangement of Xihoumen Bridge（Unit：m）

4.1 Main Technical Characteristics

4.1.1 Research on Wind Resistance

Due to frequent typhoons, the design wind speed for flutter considerations is 78.7 m/s. Aerodynamic stability is thus the main consideration and challenge of the design.

Three cross section types, namely a central-slotted twin-box section, an open-grid twin-box section, and a single box section, with girder depths of 3.5 m, 3.5 m and 5 m respectively, were investigated. Wind tunnel tests demonstrated that all three stiffness girder sections satisfied the requirements of wind resistance. Based on a comprehensive comparison, the twin-box section was adopted for the stiffening girder.

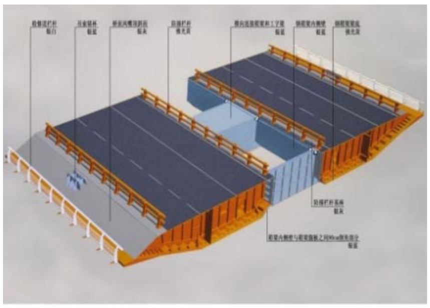

Fig.8 Segment of Main Girder of the Xihoumen Bridge

After its completion, the Xihoumen Bridge will be the first central-slotted steel box girder (separated steel box girder) suspension bridge in the world. This type of cross-section solves the flutter stability problem of large-span suspension bridges and provides valuable experience for building such bridges in the future. The use of central slotted systems is currently being studied for several other bridges in the world, including the Messina Straits Bridge in Italy, Tsing Lung Bridge in Hong Kong, and the Gibalatar Straits Bridge in Spain.

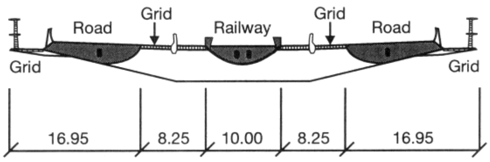

Fig.9 Section of Main Girder of Messina Strait Bridge

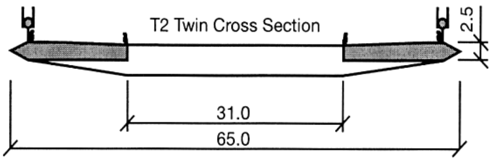

Fig.10 Section of Main Girder of Gibalatar Strait Bridge

4.1.2 Design and Erection of the Separated Steel Twin-box Girder

The Xihoumen Bridge is the first use of the separated steel twin-box girder in large-span suspension bridge construction. Its force transmission and mechanical characteristics are different from those of a conventional steel box girder. The transverse force transmission members are key components and it is important to ensure the smoothness and effectiveness of the load path for transverse force. In consideration of the force requirements during both erection and operation, transverse connecting box beams and transverse connecting I-shaped beams were used to link the separated box girders.

Fig. 11　Structure of Steel Box Girder

The average and minimum width of the Xihoumen Waterway are 2.5 km and 1.9 km respectively. The Xihoumen Waterway has deep water and tidal current, with maximum water depth in main channel of 80 to 95 m and maximum current velocity of 2.66 m/s to 3.65 m/s. There exist exposed buttes and submerged reefs with strong eddies. The bank slope is steep and the 20 m and 30 m depth contours are close to the bank. The topography near the bridge site changes rapidly, with weakly or slightly weathered bedrock shallow buried or exposed. Based on consideration of the these factors, the traditional anchor positioning method was determined to be unsuitable for the positioning of ships transporting steel box girders. A dynamic positioning method was used instead.

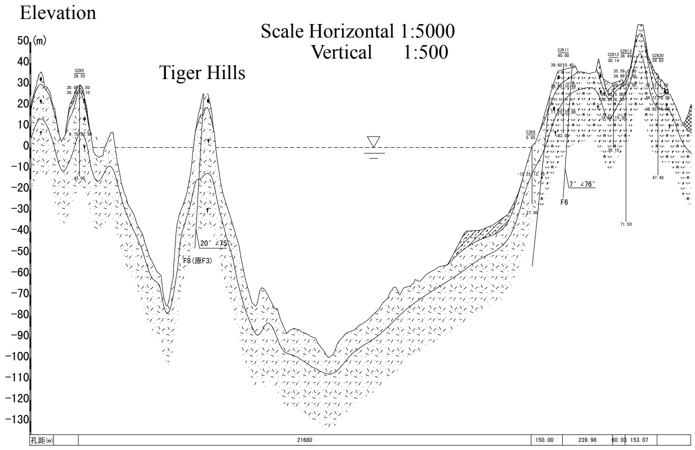

Fig. 12 Engineering Geological Profile at Bridge Axis

Fig.13 Dynamic Positioning of Ship for Transporting Steel Box Girders

The ship transporting steel box girders segments was positioned in two ways. For girder segments to be erected close to shore, the ship berths using mooring piles. For the remaining 105 girder segments, to be erected over deep water, a self-propelled barge is used and positioned using the dynamic positioning method. A 60 m self-propelled deck barge is used, with full load displacement of 2386 t and double-helm double-engine configuration (each engine 360 kW), GPS navigation and radar telecommunication system.

4.1.3 New Technology of Towing Pilot Cable Across Sea by Helicopter

The sea environment (submarine topography, sea current, sea waves, and winds) around the Xihoumen Bridge is complex. Since the channel is used by both international commercial shipping as well as the Chinese Navy, it cannot be closed or interrupted. Therefore, the traditional methods of towing a pilot cable across sea are not suitable for the Xihoumen Bridge.

Fig.14 Towing Pilot Cable Across Sea by Helicopter

The technology of towing a pilot cable across the sea by helicopter was investigated during the design of this bridge. The cable placing system for the Akashi Kaikyo Bridge in Japan was placed under the helicopter, adapted for the Xihoumen Bridge through the innovation of separating the cable placing system from the helicopter. This reduces the load and the modification expense of helicopter. In addition, a light and flexible cable placing system featuring fast cable placing, cable retracting, braking, and temperature reduction was developed. The towing of the pilot cable by helicopter was carried out successfully on August 1 of 2006, and was accomplished in 23 minutes.

4.1.4 Domestic 1770 MPa Main Cable Wire Strands Used in a Long-Span Suspension Bridge

Increasing the strength of the main cable can reduce its dead load, thus lowering cable force, reducing the size of pylons and anchors, reducing the number of wire strands of the main cable, shortening the construction period, and thus improving overall economic efficiency.

If parallel steel wires of 1670 MPa strength had been used for the main cable of this bridge, the dead load of the main cable would have been 34% of the total dead load. The performance standards of the 1770 MPa steel wire developed for this bridge have exceeded those for similar products, enabling this critical component to be procured domestically.

4.1.5 Manufacturing Technology of Suspender Cables for Long-Span Suspension Bridges

Steel wire rope of 6x37 point-contact structure was often used ten years ago. During the working process of this kind of steel wire rope, large contact stresses occur between individual steel wires in a given strand. When the suspender cable is bent, additional secondary bending stresses are produced in the steel wires which reduce fatigue resistance. The capacity of steel wire strands is relatively low due to large inner void and the small filling factor of metal. Being one of key materials for the Xihoumen Bridge, the steel wire rope used for the suspender cables should have large diameter（Φ88mm）, high strength (1960 MPa), high breaking force and good anti-fatigue performance, but there is no successful example of this type of product either at home or abroad. By designing and optimizing the structure of steel wire rope (8×55SWS+IWR) and developing heavy high-speed twistless controlled cooling rod products and precise twisting and controlling technology of wire rope and strand, the contradiction between high strength and high toughness, strand friction and anti-fatigue performance of steel wire have been solved successfully, thus overcoming the difficulties in designing and manufacturing large-diameter high-strength steel wire ropes.

5 Jintang Bridge

The Jintang Bridge, the fifth sea-crossing bridge of the project, links Jintang Island of Zhoushan City with Zhenhai District of Ningbo City. The bridge is 21.029 km in total length (18.415 km over the sea), and consists of main navigation spans, east navigation spans, west navigation spans, non-navigation spans, the approach bridge in the shoal area, the approach bridge at the Jintang side, and the approach bridge at the Zhenhai side as well as connecting bridges. The Jintang Bridge is a major four-lane expressway bridge with design speed of 100 km/h.

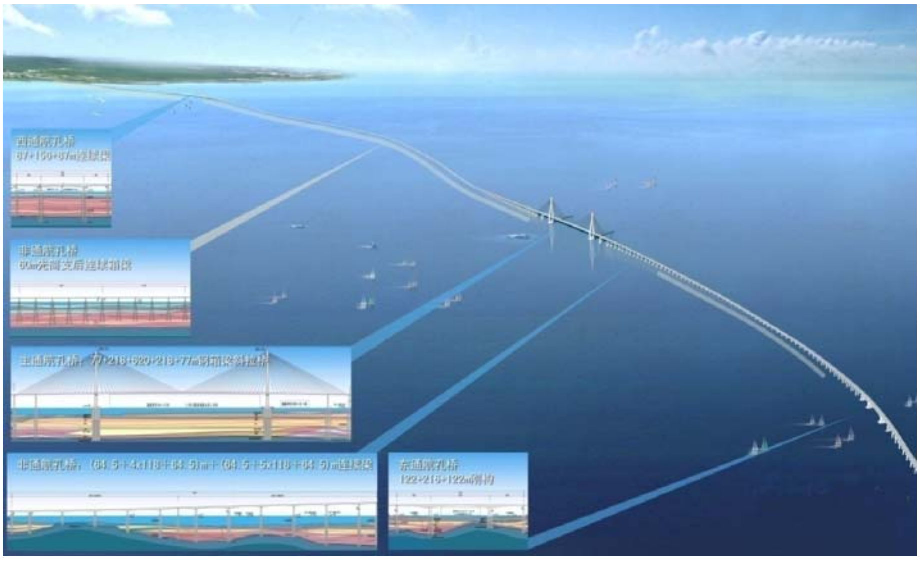

Fig.15　Birdview of Jintang Bridge

Table 3　Construction Scale of the Jintang Bridge　　Unit：m

Scheme / Item	Bridge type（m）	Foundation
Main navigational span	Steel box girder cable stayed bridge： 77+218＋620+218+77=1210	Bored pile
East navigational span	Prestressed concrete continuous rigid	Bored pile

		frame bridge：122+216+122=460	
West navigational span		Prestressed concrete continuous girder bridge：87+156+87=330	Bored pile
Non-navigational span	East navigational span～Main navigational span	Prestressed concrete continuous girder bridge：6×50+18×60+（64.5+4×118+64.5）＋（64.5+5×118+64.5)＝2700	Bored pile
	Main navigational span～West navigational span	Prestressed concrete continuous girder bridge：149×60=8940	Steel pipe pile
	West of west navigational span	Prestressed concrete continuous girder bridge：68×60=4080	Steel pipe pile
Approach bridge at Jintang side		Prestressed concrete continuous girder bridge：10×30+14×50=1000	Bored pile
Approach bridge at Zhenhai side	Shoal area	Prestressed concrete continuous girder bridge：5×60+6×50=550	Bored pile
	Land area	Prestressed concrete continuous girder bridge：（45+72+45)＋48×30+（30+2×45+30)＝1752	Bored pile
Total length of bridge		21029	

The main navigation bridge is a double-pylon double-cable-plane steel box girder cable stayed bridge with a main span of 620 m. (Fig. 18)

Fig. 16   Main Navigation Spans of the Jintang Bridge

5.1 Main Technical Characteristics

5.1.1 New Anchorage Technology for Pylon End

There are three traditional cable anchorage types for pylons, namely, ring prestressing type, steel anchorage box type, and steel anchorage beam type. The ring prestressing type has low cost and low reliability. The steel anchorage box type has advantages of convenient construction and reliable structure, with the disadvantages of unclear force distribution and the large tension in pylon wall. This system is not suitable for use in sea-crossing bridges due to concerns for durability in the harsh marine environment.

The steel anchorage beam offers clear force distribution minimal tension in the pylon walls. Traditional steel anchorage beam details, such as those used on the Annacis Bridge and the Nanpu Bridge, are not applicable for cable-stayed bridges with inclined cable planes. In addition, the concrete brackets used to support the steel anchor beams increases the duration of construction.

The Jintang Bridge incorporates an innovative detail combining the steel anchorage beams with steel brackets, which is suitable for use with inclined cable planes.

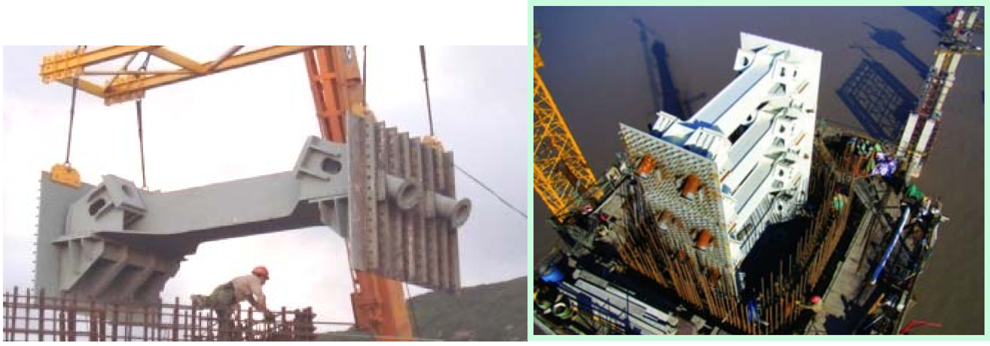

Fig. 17 Composite Structure of Steel Bracket and Steel Anchorage Beam

The force distribution induced in the pylons by this new anchorage structure is clear: horizontal force is carried by the steel anchorage beam and vertical force is transferred to the pylon shaft. Tension in the pylon walls is low, which enhances durability. The combination of steel anchorage beam and steel bracket makes construction easy and quick.

5.1.2 Research on New Wet Joint for Pier Body

Wet joints are used for the connection between the piers and pilecaps of the non-navigational spans. The concrete in the wet joints is liable to crack due to large restraint stresses caused by its upper and lower concrete and from the temporary support inside the wet joint. Cracks of different size have already occurred on the surface of wet joints in similar works built or under construction in our country.

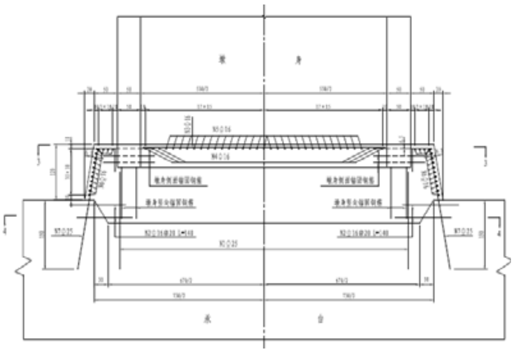

Fig. 18 Structure of Common Wet Joint

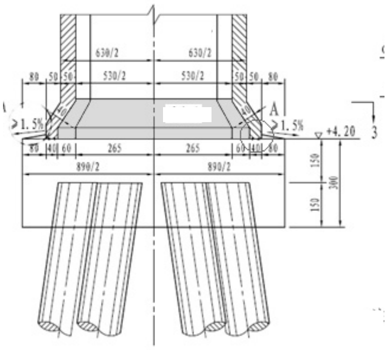

Fig. 19 Structure of New Wet Joint

In order to avoid the effect of waves on the wet joint during the construction period, the scheme of a wet joint enclosed by the pier shaft was adopted for the first time, with steel bars connected inside the pier cavity of the shaft. Steel legs are proposed for the pier shaft to reduce the restraint surface of the wet joint. The pilecaps are not dented for the sake of convenient construction. Inspired by the shield tunnel design concept, two sealing strips are set at the joint surface of precast pier body and the platform, with other joints filled by joint-filling materials. The top of the wet joint is cured after the initial set of the concrete. The pouring amount of cast-in-situ concrete for the new type of wet joint is 15.9 m^3 , only 38% of the concrete that would have been used for a conventional wet joint, this reduces the risk of cracks.

5.1.3 Automatic Controlling Technology of Curing 60 m Precast Box Girders by Vapor

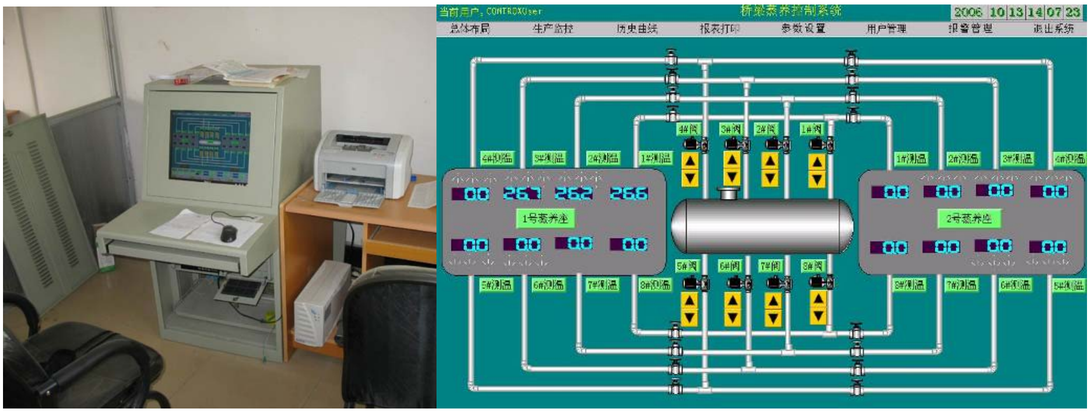

Fig. 20 Automatic Control System for Curing 60 m Precast Box Girders by Vapor

Research has been conducted on curing large volume and large tonnage concrete components such as the 60m precast box girder spans using automatic vapor curing technology. The “Multi-point measurement in large range and stage controlling” method was developed and used for this high-performance vapor curing system. Full automatic controlling technology has been applied to control the curing temperature in static curing stage, temperature rising stage, constant temperature stage and temperature reduction stage strictly and accurately according to the curing curve. Relative temperature differences between the two ends and the midspan region of the inner girder body, and the inner side and the outer side of box girder have been limited to 10℃, with the objective of reducing minor cracks and improving the quality and construction efficiency of the box girder spans.

5.1.4 Combined Handling Technology Using Two 900 t Tire Transporters

There are two options for transferring large full-span precast box girders from the precasting yard to a ship. Rail transporters are mature, low cost technology but are inflexible with regard to site planning and require a large investment in foundations, which adds to construction cost. These disadvantages to not apply to tire transporters. This option, however, requires a pair of transporters working in a coordinated manner. However, the relative position of these two transporters needs to be controlled precisely.

Two DLT900 tire transporters are used to lift a 1600 t concrete box girder, for which a synchronized control system is used to ensure the two transporters move at the same speed. The DLT900 transporter can rotate in-place by 90 degrees through eight groups of hydraulic jacks and can move a box girder to any location in the yard, with flexibility and convenience. Two transporters can work in various modes, moving forward, diagonally, or transversely to transfer box girders from yard to ship.

Fig. 21 DLT900t Tire Transporter

Fig. 22 Box Girder Onto Ship

By utilizing advanced equipment like DLT900t transporter, the precasting yard for the Jintang Bridge can be arranged more compactly. This not only reduces the area of the yard but also increases efficiency of production. At present, the maximum monthly production is 37 pieces, which satisfies the demand of the construction of the Jintang Bridge.

5.1.5 Applying Single-task Erecting and Handling Technology in the Erection of 60 m Precast Box Girders

The single-task erecting and handling mode is used for handling 60 m box girders for non-navigational spans of the Jintang Bridge. Two barges are used to handle box girders, and a Fenjin floating crane with capacity of 2600 t acts as the erection ship. The Fenjin floating crane is a non-propelled, irrotational, amplitude-changeable steel ship with separated hanger. Its main dimensions are 104x41x7.6 m, maximum draft is 6.374 m, maximum hoisting height is 80 m over water and maximum hoisting weight is 2600 t.

Because the floating crane is not used for transporting box girders, it can erect 4 to 6 pieces of box girders of 2 to 3 spans after it is anchored at a certain position, thus reducing the times of anchoring. Since 2 to 3 hours are required to anchor a floating crane, this kind of construction technology can dramatically improve construction efficiency and safety. Currently, the maximum record of erecting box girders on the project is 3 pieces per day.

Fig. 23 Installing a 60 m Box Girder Using a 2600 t Floating Crane

6 Conclusion

The Xihoumen Bridge and the Jintang Bridge are to be opened to traffic at the end of 2009. The tasks of construction management, design, construction, scientific research, supervision, monitoring, testing, and measuring of the two bridges are all undertaken by domestic enterprises and institutions, and the main construction, testing and measuring equipment, raw materials can all be supplied by domestic manufacturers, which indicates that bridge building technology in China is becoming more mature, having met the internationally advanced standard of building super large bridges.