STEEL BOX GIRDER MANUFACTURING OF PELJEŠAC BRIDGE

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Abstract

A major construction milestone of Pelješac Bridge was reached at midnight on 29 July, 2021, as the deck was connected successfully. The extra-dosed cable-stayed bridge lies in the highly active seismic region with a designed ground acceleration $a_g = 0.34g$, so the superstructure design of this bridge abandoned the regular concrete structure with poor plasticity, compared to concrete, steel has a better capability of shocks resistance and the designer adopted a steel box-shaped girder with a quantity of steel totaling 34,700 t. This accounted for almost 50 % of the entire bill of quantities, making the manufacture of the steel structure, its shipment, and on-site installation critical components of the project. Besides, the steel structure was designed with the strictest execution class EXC4 based on EN 1090-2. The specification requested near-perfect requirements for the appearance of the steel box girder. During the production, this project made extensive use of various welding robots and automatic or mechanical equipment. In addition, appropriate welding technology and manufacturing procedures ensured the quality level of EXC4. The global outbreak of the Covid-19 pandemic as force majeure had a serious impact on the steel structure production and transportation. Due to the shortage of cargo vessels the expense of ocean shipping increased dramatically. However, the contractor, China Road and Bridge Corporation (CRBC) overcame impossibilities beyond human control and utilized a simultaneous processing strategy by two manufacturers to decrease the construction period. At the meantime, CRBC relied on the shipment resource of its parent company China Communications Construction Company (CCCC) to deal with ship shortages in the global market. As a result, the steel structure fabrication and site installation were achieved in two years successfully. The acquired experience should be treated as a reference for similar mega sea-crossing bridge projects in future.

Keywords: cable-stayed bridge, steel box girder, automatic welding, EXC4, Covid-19

1 Introduction

The extra-dosed cable-stayed bridge is located in the southern part of Croatia and crosses the Mali Ston Bay in the Adriatic Sea, connecting the mainland with Pelješac peninsula. The project was majority funded by the European Union (85 %) and constructed by CRBC since the summer of the year 2018, which started from the stake number K1 + 300 and ended at K5 + 240, with a total length of 3.94 km, including the Pelješac Bridge and access roads at both sides [1]. The multi-span extra-dosed cable-stayed bridge is 2440 m long with the corresponding stake number from K2+138 to K4+542, and its access roads on the mainland (K1+300 to K2+120) and the peninsula (K4+560 to K5+240) are 820 m and 680 m respectively. The bridge has the whole layout of 84 +108 +108 +189,5 + 5 x 285 +189,5 + 108 + 108 + 84

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= 2404 m, and the total length of the bridge including abutments was 2440 m. See Figure 1 The massive abutments U1 and U14 are located on opposite shores, pier S2 on land adopted 11 m-diameter and 8 m-high circular extended foundation and pier S13 located on the border between land and sea and applied 22 drilled 1.5m-diameter overlapping piles foundation[2], the other piers S3 to S12 are located in the sea and adopted extra-long steel tubular piles[3]. The main span structure is from pier S5 to S10. The average water depth is 27 meters [4]. The superstructure consists of steel box-shaped girders with a total quantity of steel of approximately 34,700 tons. The bridge lies highly seismic region with a designed ground acceleration a_g= 0.34g. However, steel as raw material has a better capability of toughness and shock resistance than brittle concrete. Its design is suitable for high-frequency seismic regions. The steel box girder occupied nearly half of the bill of quantities of the whole project. Achieving such a large amount of steel structure fabrication within such a short period is a massive challenge for any contractor in the world.

Figure 1 The completed Pelješac bridge (March. 2022) Credit: CRBC

2 Design work

The steel box girder in this project is designed as a three-cell box with a 22.5 m-wide orthotropic deck plate, its bottom plate is 8.1 meters wide and both side bottom plates are inclined 24 degrees towards the horizontal direction, lowering the drag coefficient and ensuring the aerodynamic stability without wind protection. The box girder is 4.5 m tall, corresponding to a depth-to-span ratio of around to 1/64, its middle narrow cell is 3 m wide, as it corresponds to the width of the central 3.5 m-wide concrete curb on the deck. See Figure 2. The deck plate is 14 mm, and it becomes up to 20 mm thick in the area of stay cables and above the piers [2]. The horizontal distance between the anchor points on the deck is 12 meters, so each pylon has 10 couples of 12 meter-long standard box girders, the total length of the girder with stay cables is 1440 m, the total length of the rest of the steel box girder without stay cables is 890.8 m. The segments of side span at sea are divided into several extra-long segments with lengths ranging from 36 to 56 m respectively, which were installed by a 1000 t-capacity floating crane. There are a total of 7 closure segments, the main span's closure space is 18.6 m long, and the closure spaces between the side span and main span are 29.7 m long as seen in Figure 3. The standard segments and 7 closure segments were lifted into place by derrick cranes. The below Table 1 indicated the detailed length division of 165 steel box girders and the applied corresponding installation methods. The corrosivity category and durability range for this project were defined as C5 and VH, based on the revised specification EN ISO 12944-5: 2018 [5]. The paint system applied also complied with the updated specifications.

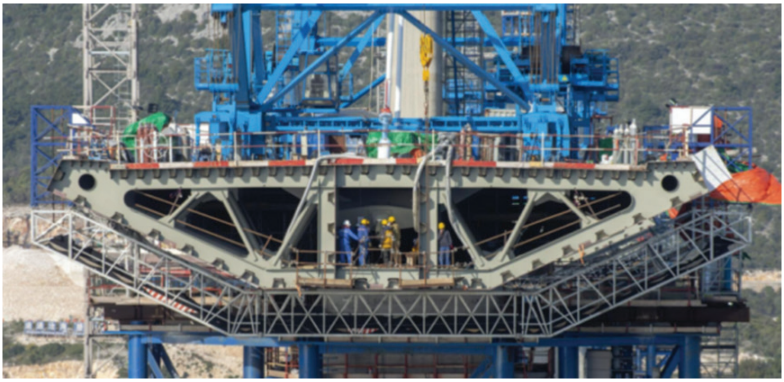

Figure 2 Standard cross-section of steel box girder with anchor box (March 2021) Source : CRBC

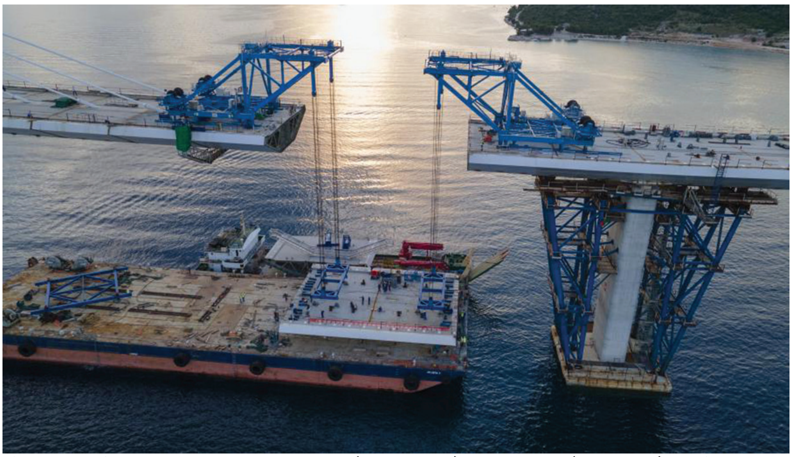

Figure 3 The first closure segment CR4 (29.7m long) installation (June 2021) Credit:CRBC

Table 1 Steel box girder division and erection methods

Type of girder	**Length of girder** [m]	**Maximal weight** [tons]	**Total number of girders**	**Erection methods**
Curved segments on land (mainland side)	8.8 m + 9 x 12 m	230	10	Floating crane and slipping along rail track
Side span large segments (mainland side)	52 m + 52 m + 56 m + 52 m	780	4	Floating crane
Main spans	6 x 2 x 10 x 12 m	220	120	Balanced cantilever with derrick cranes
Steel composited girders	6 x 2 x 9.92 m	284	12	Floating crane (1000T)
Side span large segments (Pelješac side)	52 m + 52 m + 56 m + 52 m + 36 m	790	5	Floating crane (1000T)
Curved segments on land (Pelješac side)	8.8 m + 6 x 12 m	230	7	Floating crane and slipping along rail track
Closure segments	29.7 m + 5 x 18.6 m + 29.7 m	211 / 360	7	Derrick cranes
Total		34 700	165	

3 Preparation of manufacturing

Faced with the challenge of completing a great amount of steel structure manufacturing tasks in a short period, the contractor applied a simultaneous processing strategy by two manufacturers. Besides, the contractor focused on the manufacturer's production capacity and the degree of mechanization and automation. As a consequence, the contractor selected two Chinese world-renowned steel bridge manufacturers (ZPMC and CRBBG), both of which have a combined annual capability of over 500, 000 t of the bridge steel structure. In comparison to other steel structure factories, they are particularly equipped with automatic equipment for bridge steel structures. In addition, the entire workshops and their ports were designed specifically for the bridge's steel structure products. As professional bridge steel structure suppliers, both of them acquired rich experience of European standard products. Furthermore, they obtained the required certificates, which were qualified by the European Union notified body with the execution class EXC4 according to EN 1090-2 [6] and ISO 3834-2 [7]. The raw material for the steel box girders is S355J2+N, S355K2C+N, and S460M, and the material in the region of the anchor box applied S355M when the thickness exceeds 50 mm. All the raw material was purchased from Chinese steel mills which obtained the production licenses under European CE certified standards EN 10025 [8]. The local steel mills were provided with the advantages of large plant capacity and short-haul distance so that it ensured the stable supply under the global Covid-19 epidemic situation.

4 Manufacturing procedure in the workshop

The steel box girder was made of numerous and various panels, the same type of panels were marked in the same colour as seen in Figure 4. The panels of the same type were cut, assembled, and produced on a continuous flow line. It is obvious that the U-shaped stiffing ribs were applied in the top, bottom, inclined bottom, web as well as side-web panels. Therefore, the U-rib assembly and welding procedures must be equipped with automatic or mechanized equipment, to ensure precision and efficiency.

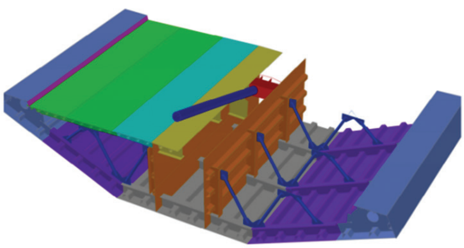

Figure 4 3D-Model of standard segment and its panels Credit: CRBC

The multiple U-rib welding robots that were previously used in marine ships, shown in Figure 5 below, at present are developed for orthotropic panels production in the field of steel bridges. This welding robots can assembly and weld up to four I-shaped and U-shaped stiffening ribs simultaneously. Its largest panel units dimension is up to 4.5 x 18 meters. Multiple U-ribs welding at the same time could provide for better control of post-weld deformation, resulting in better panel flatness. The requested welding parameters could be set and adjusted by the computer program in advance. The angle between U-rib and bottom plate could be adjusted in the range of ±30°, therefore the welding wire can reach the root, ensuring adequate penetration depth. Pelješac Bridge's U-ribs adopted argon-rich gas shielded welding procedure with solid wire. The shielded gas is made up of 80 % argon and 20 % CO_2, the arc heat is concentrated as well as the heating region is small, the argon gas has the cooling effect, controlling the deformation after weld. The less than 8 mm-thick U-rib could be completed by one-pass welding. However, a maximum of 12 mm-thick U-ribs were accomplished for root and cap by one-pass welding respectively. In this wise, the weld spatter was decreased obviously and the one-pass welding rate and wonderful weld appearance were ensured the visual inspection of EXC4. In addition, the travel speed of the U-rib welding robot is around 400 mm/min, so the 12-meter-long standard U-rib panel unit might be achieved by approximately 10 - 12 pieces per day. Both of the manufacturers are equipped with multiple U-rib welding robots, to improve production efficiency [1]. In fact, except for the mentioned U-rib welding robot, each stage of the bridge steel structure manufacturing has almost achieved full mechanization and partly automation, reducing the impact of man-made factors on processing accuracy and welding quality. This is the advantage of a professional steel bridge manufacturer, which is different from the general steel structure manufacturer.

Figure 5 The U-rib welding robots (September 2019) Credit: ZPMC

Figure 6 Various panel units assembly on the steel bed-jigs (November 2019) Source-CRBBG

When the panels were completed, they would be transferred to the final assembly workshops. The various panels were assembled on the steel bed-jigs in both workshops, as shown in Figure 6, which had dimensions of 40 x 200 m and 52 x150 m, respectively. The maximum 30 m-wide and 100 m-long steel girder could be assembled in this workshop according to the bridge's camber design. The assembled relative elevation of the bed-jigs was set by the actual longitudinal gradient of 2.98 %. Besides, each assembly round limited the number of segments to "5+1", the "1" was treated as a matching segment for the following round. Each manufacturer was equipped with two assembly workshops for this project, to speed up the assembly effectiveness. Both manufacturers started the production of panels in September 2019 and the last batch of girders was accomplished in the workshop till January 2021.

5 Site installation

The 6 main pylons were completely cast by the end of February 2021, after that, the installation of the main spans started. The 12-meter-long standard segments were raised by derrick cranes with a maximum lifting capacity of 250 tons, as indicated in Figure 7. Derrick cranes were also applied to install the 7 closure segments. In total, 6 couples of derrick cranes were adopted to the superstructure installation synchronously. A steel box girder's cyclic work of hoisting, welding, and stay cable tensioning took an average of 8 to 9 days to complete. During the installation phase, the superstructure was formed without wind barriers, to improve the stability of the whole structure, four wind-resistance cables were installed, and the superstructure was tied to the foundation. The famous "Bora" wind near the Adriatic Sea broke the meteorological record of gust speed on-site up to 50 m/s during the bridge construction.

Figure 7 Standard segments installation with by derrick cranes (June 2021) Credit: CRBC

While the standard main span segments were being erected, the side span segments were also being installed simultaneously. It must be pointed out that the adoption of the large lifting equipment to speed up the installation is the outstanding highlight of this project. There are 9 extra-large segments of both side spans in the water, which were raised into place by floating cranes directly. It must be stressed that the 56-meter-long extra-large segment weighted up to around 800 tons, when adding the temporary lifting and fastening auxiliary structures were added, the total weight was more than 910 tons. Therefore, the floating crane's maximum 1000t-capacity was almost full utilized, as indicated in below Figure 8.

Figure 8 Extra-large segment R11 installation by 1000t floating crane (June 2021) Credit: CRBC

The accurate adjustments and measurements of all the girders were carried out when the air temperature was constant at midnight. Because there was a lack of skilled steel structure workers in the surrounding regions, the contractor utilized the charter flights and arranged for around 400 Chinese high-skilled steel structure workers and engineers to be on-site to speed up the erection during the superstructure's construction. Furthermore, the workers were divided into three groups and cycled every 8 hours, ensuring a continuous 24-hour time [9]. The main work on the bridge site is the welding and anti-corrosion of circumferential seams, so the contractor provided up to 26 temporary construction platforms, as shown in Figure 2, for simultaneous construction. The last closure segment CR8 was hoisted into position on 29th July 2021 at midnight. All the welding and inspection of the superstructure on-site were achieved within five months.

6 Shipment

Both of the manufacturers are located on China's east coast and it is quite far from the bridge site in Croatia, so it's impossible that the processing in the workshop and the installation on-site could be timely synchronization, in the end, the long-distance marine shipping is unavoidable. In comparison to the suspension bridge's superstructure site installation, the cable-stayed bridge will take longer to erect since the stay cables must be installed and stressed, while the circular seam must be welded prior to the following girder erection. However, the suspension bridge's hangers could hoist all the steel girders from the ship into the air for temporary fastening. Besides, there is not an adequate storage yard for steel box girders on the bridge site. As a result, the large flat ships or semi-submersible barges didn't apply in shipment in this project, because they cannot stay on-site for an extended duration. Finally, the contractor adopted heavy lift cargo vessel, as shown in below Figure 9, whose hold and deck could be provided with more storage space, the steel box girders could be stored with two-layer overlapping in the meantime. Besides, the speed of this type of vessel is faster than the flat ships. The vessels took around a one-month-long voyage from China and routed through the regions of monsoon and ocean currents. The time gap between batches matches the demand for on-site erection. And the erection speed on-site was around 35 pieces each month. In total, 165 steel box girders were continuously delivered in 7 batches to Croatia.

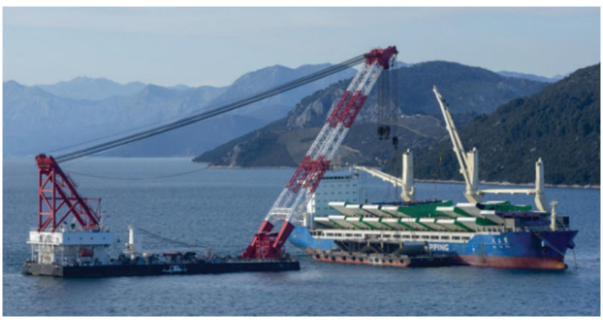

Figure 9 Unloading of steel box girders from heavy lift vessel (March 2020) Credit: CRBC

The global breakout of the Covid-19 epidemic has impacted the international shipping industry since February 2020. As a result, shipping rates are increasing due mainly to a shortage of shipping resources, and the shipping plan had to be updated on a constant schedule. The contractor mainly relied on the shipment resource of its parent company China Communications Construction Company (CCCC) to deal with shipping shortages in the shipping market.

7 Conclusion

The bridge steel structures have the advantages of rapid on-site installation, replaceability, and environmental protection. They have been commonly adopted to the mega sea-crossing bridge in recent years. The steel box girders of Pelješac Bridge were completed within two years, due to the high degree of mechanization and automation of the steel bridge manufacturers, as well as the contractor's appropriate shipping plan. Although the outbreak of the pandemic had a serious impact on the project, the contractor relied on the Chinese steel structure's whole industrial production chain, while the Chinese government's effective epidemic prevention strategies, minimized the impact on the domestic manufacturing industry, and in the end, overcame unprecedented challenges and mobilized various resources worldwide to achieve the sea-crossing bridge connection.

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