An introduction to Stonecutters bridge, Hong Kong: Erection of the steel segments, hydraulic buffers and lateral bearings

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**ABSTRACT:** Stonecutters Bridge was opened to the public in December 2009. It is the second longest cable stayed bridge in the world with a main span of 1,018m, two single towers 298m high and having a clearance of 70m, crossing the entrance to one of busiest container ports in the world. This paper introduces the erection of the main span steel segments, the back span heavy lifts, the hydraulic buffers, the lateral bearings, and briefly outlines construction of towers, back span concrete works, fabrication and assembly of the steel segments in China. The heavy lifts for the steel back spans were one of the most substantial heavy lifts undertaken on a cable stayed bridge project. Each deck section was 88m long and weighed over 4,000 tonnes. It involved extensive temporary works, partial strengthening of the permanent works and detailed design checks. Due to the complexity of the operation the JV formed an Alliance with specialist contractor VSL Hong Kong. The four hydraulic buffers, located at the front and back side of each tower are some of the largest installed on any bridge. They were required to protect the bridge against dynamic action such as strong wind actions and traffic forces. The lateral bearings worked in conjunction with the hydraulic buffers are also located both side of the towers. The Client is the Highways Department of the Hong Kong Special Administrative Region and the designer was Arup. Yokogawa Bridge Corporation (YBC) is one of four partners of the contractor’s JV which includes Maeda Corporation, Hitachi Zosen Corporation and Hsing Chong Limited who commenced the contract in April 2004. The JV’s consultant for all the construction engineering services was Maunsell (now AECOM).

1 INTRODUCTION

The striking profile of Stonecutters Bridge as seen in Figure 1 is one of new generation of long span cable stayed bridges. The main span has a unique slender twin orthotropic steel deck 53m wide linked by cross girders at 18m centres giving excellent aerodynamic performance. Extensive bridge aerodynamics investigations and wind tunnel testing were carried out by the JV’s consultant including deck section model testing, aerelastic freestanding tower model testing on different erection heights, and aeroelastic bridge model testing to investigate the bridge erection stages.

The main span segments were fabricated and assembled in separate locations in China and then brought by barge to Hong Kong. Bridge geometry control methods and procedures were crucial and the contractor, supported by the JV’s consultant carried out all the challenging technical issues for prediction, survey, re-analysis and final adjustment during the bridge erection cycle.

The segments were lifted from a barge positioned in the 900m wide main shipping channel of Hong Kong’s very busy container port. This required simulation tests with the Port Authorities before commencement, a GPS system on the barge, and a fast method to lift the segments to minimize the time the barge remained in the shipping channel.
A prefabricated parallel wire strand stay cables system was used, which reduced the effect of cable drag. Deck dampers are also being installed to minimize cable vibration. The main span lifting period went through two typhoon seasons, one of which was particularly active, and this involved contingencies at every stage to ensure that safety was not compromised.

Figure 1: General View of Stonecutters Bridge

2 TOWER AND CONCRETE BACKSPANS

2.1 Towers

The reinforced concrete towers start as an oval 24m across at the base and reduce to a circular cross section 7m diameter at +175m level and were built using a jump form system. The upper tower then becomes a composite structure with a stainless steel outer skin and inner steel anchor boxes for the stay cables. Figure 2 shows a typical arrangement for the three component parts. Both 56 No. steel anchor boxes for the cables and the duplex stainless steel skins were manufactured at the same yard in China and great care was taken to ensure the geometry was correct (See photograph 1). After fabrication, trial assemblies were carried out on three sections of the combined units to check for verticality, and so ensuring a good fit on site. The stainless steel skins and anchor boxes were erected by using a tower crane with lifting capacity of 26 tonnes. See photograph 2.

Figure 2: Upper Tower Composite Structure

Photograph 1: Trial Assembling of Stainless Steel Skins
2.2 Concrete Backspans

The 289m long back spans shown in Photograph 3 are reinforced concrete acting as the counterweight to the main span and supported by four piers either side between 60 and 70m high. Construction of the concrete back spans was extremely challenging since the structure was unable to support itself until the stay cables were installed and stressed, making it necessary to have a large scale falsework system in place for more than two years.

3 FABRICATION AND ASSEMBLING OF STEEL SEGMENTS

3.1 Fabrication of the Segments

65 No. steel deck segments weighing a total of 33,200 tonnes were fabricated from high grade S420M or S420ML rolled steel plate in accordance with BS EN 10113 which was procured from Japan and Europe. The fabrication was undertaken by a major Chinese fabricator CRSBG at their facilities at Shanhaiaguan in Northern China who also fabricated Sutong Bridge, the longest cable stayed bridge in the world.

The segment plates varying in thickness from 10 to 40mm were rolled and cut, and the U-troughs, T stiffeners and anchor boxes added. All the welding was by CO2 (gas shield) arc welding. The most critical components were the stay cable anchor tubes which had to be fixed to the segment with an accuracy of 0.1 degrees. The sub sections were then transported to the local port and then by ship to the assembly yard near Dongguan on the Pearl Delta, on the southern tip of China close to Hong Kong.

3.2 Fabrication of the Segments

There were two production lines set up in the assembly yard, one for each side of the bridge, which were able to handle up to eight segments at a time. The sub sections were assembled into segments on the production lines and all temporary fixings required for lifting attached. Trial assemblies were carried out in batches of three segments to ensure that when the segments were erected on site that the geometry was replicated. Due to the different support conditions of the adjacent segments during erection it became necessary to fix temporary bowstrings on the top deck of the segment to allow final geometry adjustment after lifting.

Once the trial assemblies were completed the segments were sent to the adjacent blasting and painting shop. The traditional paint system for the external surfaces consists of an organic epoxy zinc rich primer, two coats of micaceous iron oxide (MIO) and a coat of polyurethane totalling 400µm thickness. A final coat of polyurethane is applied at the bridge site. The internal surfaces only have one coat of primer as there will be a dehumidification system installed inside the main deck.

After painting, a first stage fixing of ancillary works was carried out and the completed deck segments 55m wide and 18m long weighing around 500 tonnes each were placed by multi-wheeled transporters onto a purpose built barge and towed to Hong Kong.

The assembly cycle for a segment was approximately 60 days. Storage of the segment was required at the assembly yard. The logistics of positioning the units in the storage area were closely monitored to ensure that the segments were available in the correct sequence to meet the site programme.
4 ERECTION OF BACKSPAN STEEL SEGMENTS

4.1 Introduction
The backspan steel deck segments were located over land and a so different method of erection was required to the main span. An initial proposal was to build a substantial falsework system out from the tower so that the units could be lifted from a barge and slid back into position at deck level. However this scheme was no longer possible due to programme constraints and it was replaced by an alternative scheme developed by an Alliance of JV with VSL. This was to assemble the segments on the ground adjacent to the towers and have one heavy lift at each tower. This required structural verification of the permanent works and was carried out by the JV’s consultant who also determined additional strengthening measures and detailed geometry control procedures.

4.2 Preparation Works
Existing tetrapod sea defences were removed in front of the towers, and jetties formed from precast concrete blocks with concrete platforms laid out behind them. In addition a large unloading frame was erected cantilevering from each tower, with temporary stay cables supports anchored back into the tower. See Photograph 4.

4.3 Assembling of Backspan Segments on site
The two steel back span sections each comprised of six segments and these were brought in their basic parts of longitudinal girders and cross girder, by barge from China. They were lifted by the unloading frame from the barge onto carts and slid on rails by hydraulic jacks to their lifting position. The alignment and elevation relative to each other were fixed and the longitudinal girders of the seven segments welded together.

Strand jacks were mounted on brackets attached to the towers which was also supported by temporary stay cables anchored back into the towers. At each tower the two longitudinal girders weighing approx 4,000 tonnes which included the two main span lifting gantries, were lifted simultaneously to ensure a balance of load between the brackets on the tower.

The load distribution between the tower brackets and the deck lifting frame was about 80:20. Guides were attached to the tower and to the back span concrete falsework system to restrict the lateral movement during the lift, and the wind speed was closely monitored at all levels during the lift-see Photograph 6 and 7.

4.4 Heavy Lifting and Sliding of Backspan Girders
The deck was initially raised to approximately 50m above ground level in a series of 0.5m strokes of the strand jacks. At this level, due to the tapering geometry of the tower the decks had to be slid laterally 4m towards one another.

The lift then continued until the girders were at deck level about 75m above ground level. They were slid laterally again 2m and finally 2m longitudinally to match up with the back span. This was a very delicate operation and achieved the stringent tolerances required.

Extensive surveys were carried out to achieve the fine assembly tolerances for the cross girders. After confirmation, the five cross girders were then lifted up by strand jacks individually and welded into position.
The next stage was the load transfer from the deck lifting frame on the concrete back span to the interface truss, which was part of the back span falsework and supported the end of the concrete deck and the end of the steel back span. When the load transfers were complete the concrete stitch was cast and stressing carried out between the steel deck and the concrete deck. With the stitch complete and the cross girders welded, the permanent stay cables could be installed. This lifting operation was successfully carried out for the east back span first, and then repeated on the west back span, each time taking less than two days.

5 ERECTION OF MAIN SPAN STEEL SEGMENTS

5.1 Marine Works

Extensive preparations were required for the main span erection due to the restraints of maintaining the flow of shipping through the busy shipping channel during construction. A coordination team was set up at the beginning with the Marine Department to liaise with all the various parties in the container port and regular meetings held to keep the parties informed on the latest methods and programmes. Simulations of the barge movements were carried out in conjunction with the port’s shipping pilots using a local simulator. Checks were carried out on how the lifting operations would affect the movements of the vessels and particularly the berthing and departure of the large container ships from the adjacent berths which on the west side were only 20m from the tower jetty. This worked very successfully with no marine incidents recorded during all the lifting operations.

The choice of barge carrying the segment was also critical. It had to be self-propelled, could not use anchors in the channel and be capable of being dynamically positioned. In addition its depth was limited by the shallow waters at the jetty and length limited by the restraints of the jetty. It also has to be capable of sitting on a support platform for loading operations in China when the segments were loaded by multi wheeled loaders which required additional stiffening in the hull. As a result it needed to be purpose built and was 76m long, 21m wide and 4m deep and constructed in a yard in China – see Figure 3.
After loading the segment, it was towed by tug from the China assembly yard and used GPS satellites for final positioning and holding its position by means of thrusters located at the four corners of the barge. Current measurements were taken in the channel during the year before commencement of lifting and a current atlas prepared to predict for every deck lift operation.

![Figure 3: Dynamic Positioning Barge](image)

5.2 Lifting Operations

Lifting operations were carried out on a 10 to 12-day cycle with the lifting alternating between the east and west side of the bridge. The lifting area was 200m by 200m and this was cordoned off by four guard boats. The barge would be towed to the lifting area and position for lifting using the GPS system and checked by surveyors. The lifting was carried out by lifting gantries positioned on the end of the deck. The gantries were designed optimising the weight to 200 tonnes to reduce the deflection in the deck as much as possible. The winches were supplied by Yokogawa and were linked and computer synchronized for load and level and used in preference to strand jacks as they were faster, lifting the 500 tonnes segments in under 40 minutes, and gave a smoother operation. Photograph 8 shows a deck segment being lifted.

![Photograph 8: Lifting Main Span Segment](image)  ![Photograph 9: Last Stage of Canti-lever Erection](image)

The lifting gear was lowered from the lifting gantry and attached to the segment lifting lugs. Once secured the lifting frames took the load until the segment just lifts off. At this point wooden wedges beneath the segment are immediately removed to avoid rebound and potential resonance between the barge motion and the deck cantilever. The segment is lifted smoothly until reaching deck level when the barge can depart.
5.3 Connecting up of Segments

The support conditions of the lifted unit were different to the erected unit, which was also deformed by the lifting gantry, and so special measures were required to enable the units to be matched. It was therefore necessary to deform the lifted twin box segment in a similar manner and this was achieved by using an External PT system (bowstring). Figure 4 shows the arrangement. It consisted of posts either side of the cross girder with two steel sections connecting the posts and diagonal PT bars fixed to the deck plate. It was attached at the assembly yard, and after lifting the load was applied by means of hydraulic jacks at the base of the posts which introduced a transverse deformation on the segment. The load was adjusted until the deck plates of the lifted segment matched those at the cantilever end.

Figure 4: External PT system on lifte-in segment

Access gantries were required for both access for the welders and for installation of the stay cables. After final positioning of the deck segment the gantry was moved forward up to the connection joint. Keeper plates, which had been sent from the assembly yard with the segment, were then fitted to match up the perimeter, and after checking the alignment of the stiffeners and the final perimeter gap, it was ready for welding. The sequence of the perimeter welding was important to minimize any distortion to the deck plates and once commenced it had to continue to completion which was generally less than 24 hours. Whilst this welding was being carried out, the back span cables could be installed and stressed. The stiffeners across the erection joint were then fitted and welded, the bowstring prestress system removed, and the main span stay cables installed and stressed.

The main span lifting gantry meanwhile was being prepared to move forward on a jacking system and bolted down to the deck of the new segment, and the cycle was ready to start again. The highest risk during the construction of a long span bridge is a typhoon striking during lifting operations, and Stonecutters Bridge lifting programme went through two typhoon seasons. So it was necessary to develop typhoon contingencies for all stages of construction operations. A temporary system of bolted connections which could be fixed across the erection joint in 24 hours was developed by the erection team in case the welded perimeter joint could not be completed in time. Vertical buffeting of the cantilever before the leading main span cables be installed was also considered, which would lead to a possible overstress situation in the deck. A longitudinal bowstring system was developed for the longer cantilevers. Neither of these contingencies were ever required.

5.4 Stay Cable Fabrication

Prefabricated parallel wire strand stay cables (PWS) were specified for this bridge because of the compact form which reduces the area exposed to wind and so reduce the effect of cable drag. The cables were produced by Nippon Steel Corporation in their jointly owned factory at Jiangyin near Shanghai which was one of the few factories in the world capable of fabricating cables of this length. A typical cross section is shown in Figure 5 comprising of 7mm galvanized wires with a tensile strength of 1,770MPa. A dimpled finish was adopted on the sheathing and further tests were carried out on the watertightness of the cable. Hydraulic dampers were installed on the deck to minimize vibration with rubber dampers in the tower anchorages.

The wire for the cables was manufactured in Japan, and it was cold drawn and galvanized at another Nippon Steel’s factory in Jiangyin. A gauge wire was extended on the assembly bed under a predefined load and the length established. The remaining wires were then pulled and the cable twisted and wrapped with filament tape. The cable continued on the production line and was fed through an extruding machine to form the 10mm thick HDPE coating, and finally through a dimpling machine before being wrapped. The stay cable socket was cast in a separate factory from a steel alloy 41Cr4. The wires were pulled through the socket and anchored to an end plate. The socket was heated and filled with socketing material of steel balls, rock dust and epoxy resin before being heated to 180 degrees C. It was then given an initial stressing before final wrapping on steel reels and transported to site.
5.5 Stay Cable Installation

The cables were delivered by ship to site and the length and weight meant that the craneage and handling equipment was much larger than that required for parallel strand stay cables. Japan has had a lot of experience with these cables and specialist plant was available through Yokogawa. The shorter cables could be lifted directly from ground level to deck by mobile crane but longer cables required a gantry crane mounted on the deck. The cables were stressed from the deck anchorage and a typical arrangement is shown in Figure 6.

The tower socket was lifted by the tower crane in tandem with a deck mobile crane and fed into the tower anchorage. The deck socket required two mobile cranes for feeding the cable through the anchor tube whilst tensioning devices are required on deck to pull the cable longitudinally. With the longest cable weighing 77t and 541m long this required great care to ensure there was no excessive bending of the cables or damage to the HDPE coating. The largest cable had 499 wires 7mm diameter with a breaking strength of 34MN. The specialist stressing jacks were provided by Yokogawa and the cables were stressed to length, not load, although checks were carried out on the actual cable load to check against the predicted loads. The jack capacity was 1,400 tonnes with a stroke of 350mm.

For each erection cycle the deck profile was predicted with the stay cable loads. After the leading cables were stressed a detailed night survey was carried out. The survey covered the position and elevation of fixed points on the deck, deflection of the towers, temporary load conditions and temperature and wind conditions at selected locations on the deck and towers. At the same time the stay cable loads were determined by measuring the frequency of the cables under ambient vibration. The results were passed to the JV’s consultant for
back analysis and prediction, in order to make an immediate evaluation whether any adjustments were re-
quired to the cable lengths. This was carried out by increasing or decreasing the deck anchorage shim plates.

One additional challenge occurred when, after checking the final delivery of cables, three cables were
found to be damaged, which had occurred on the ship during a violent storm in the South China sea en route
for Shanghai. The HDPE sheathing had been punctured and there was some damage to the galvanized wires.
The decision was immediately taken to replace them but, after checks with the manufacture, it was decided to
use them temporarily until the new cables arrived. This meant that the cables had to be replaced using a new
method and different erection platforms to allow for the surrounding cables already erected. This was
achieved and there was minimal disruption to the site programme.

6 HYDRAULIC BUFFER AND LATERAL BEARINGS

Systems
The four hydraulic buffers located at the front and back side of each tower are some of the largest installed on
any bridge. They are installed at deck leve between the tower and nearest cross girders and rigidly support
longitudinal dynamic actions such as strong wind forces and traffic forces whilst they allow slow movement
of thermal deck movement. The lateral bearings work in conjunction with the hydraulic buffers and are also
located both side of the towers. They support transverse horizontal forces acting on main girders and stay ca-
bles. Also they restrain transverse movements at the towers.

![Figure 7: General Arrangement of Hydraulic Buffers and Lateral Bearings](image)

![Photograph 11: Around the Tower](image) ![Photograph 12: Hydraulic Buffer](image)