Stonecutters Bridge – Detailed Design

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Summary

Highways Department (HyD) of Hong Kong SAR is going to build a bridge across the entrance to Kwai Chung Container Port. Due to the spectacular location HyD decided to procure the concept for the bridge through an international design competition. The competition took place in the first half of 2000 and the winning scheme was a cable-stayed structure with freestanding towers located between twin box girders. The 1018m main span is in steel, while the four back spans each side are in concrete. The two towers stand on shore, providing unobstructed access to the busy container port with minimum navigation headroom of 73.5m. A number of modifications were introduced to the scheme during subsequent technical review. Detailed design started in March 2002 and tender was called in August 2003 and returned in December 2003. Completion of the bridge is scheduled for mid 2008. This paper concerns the detailed design.

Keywords: Cable-stayed bridge; twin-box deck; freestanding central tower; stainless steel; composite construction; orthotropic steel deck; prestressed concrete.

1. Introduction

Stonecutters Bridge is part of Route 9, an east-west expressway providing a further link between the Hong Kong International Airport at Lantau Island and the urban areas of West Kowloon. The Tsing Ma Bridge and Kap Shui Mun Bridge completed in 1997 also form part of this route.

Fig. 1 Location of Stonecutters Bridge

Fig. 1 shows the Route 9 alignment and the bridge location. The bridge concept resulted from an international design competition, which took place in 2000 [1]. The consultancy for the detailed design was awarded to Arup and COWI in March 2001. Thorough technical review of the Reference Scheme led to a number of modifications [2] whilst maintaining the visual appearance of the concept. Detailed design commenced in March 2002.

2. The Bridge

Stonecutters Bridge is cable-stayed with a total length of 1596m. It has a main span of 1018m across Rambler Channel and four back spans each side of 79.75m, 70m, 70m and 69.25m. The freestanding towers are in concrete up to level +175m and in steel-concrete composite from level

+175m to level +293m with the outer steel skin being stainless steel. The top 5m is a glass covered steel structure, which acts as an architectural lighting feature and provides storage space for maintenance equipment. The 2 planes of stay cables take a modified fan arrangement, anchored at the outer edges of the deck at 18m spacing in the main span and 10m spacing in the back spans.

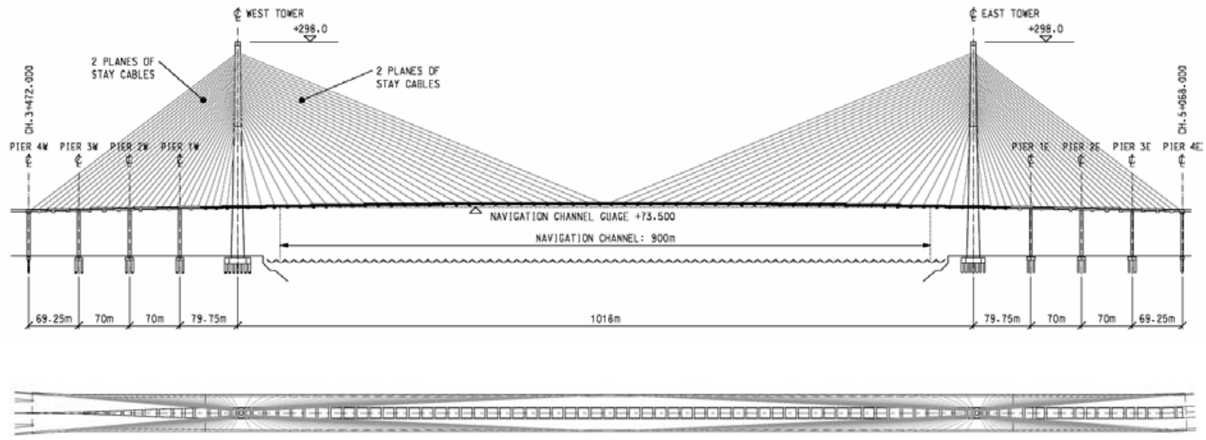
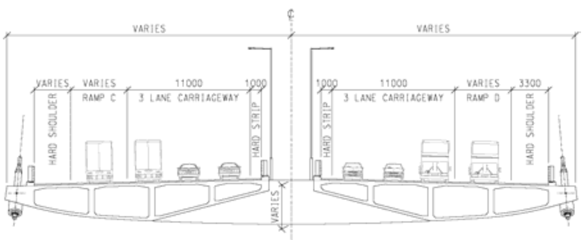


Fig. 2 Stonecutters Bridge - Plan and Elevation



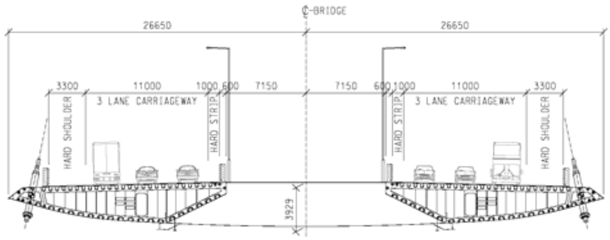


Fig. 3 Concrete Deck – West Back Spans *Fig. 4 Steel deck – Main Span*

The bridge deck is a twin-box girder, steel in the main span and prestressed concrete in the back spans. The interface between steel and concrete is positioned 49.75m into the back spans as a result of optimisation studies. The two longitudinal girders are connected by cross girders. The alignment of the main span is straight and the deck width constant. However, the back spans have to accommodate widening carriageways at the western end and a curved alignment with superelevation at the eastern end.

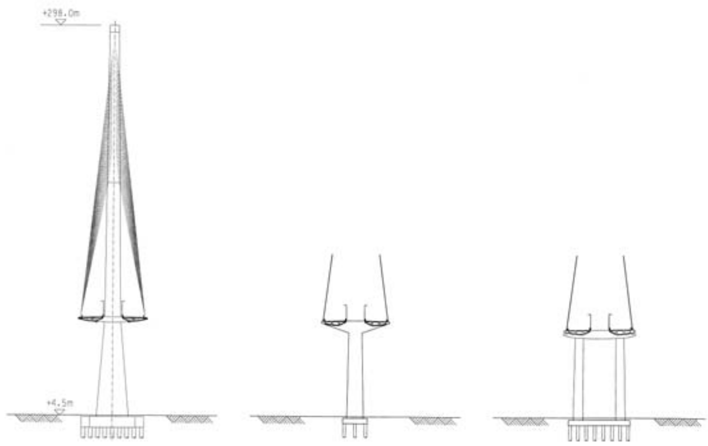


Fig. 5 Tower and Piers

The piers in the back spans are monolithically connected to the bridge deck. The three intermediate piers are single column piers, while the end piers at the adjoining viaducts are twin column portal structures. Laterally the bridge deck is restrained by vertical bearings on the towers and by the back span piers. In the longitudinal direction restraint is provided by hydraulic buffers at the towers and the back span piers. The buffers are set such that movements due to static actions such as temperature and mean wind can take place while short-term dynamic actions due to wind buffeting and seismic activity are resisted.

The ground each side typically comprises a highly variable thickness of superficial deposits overlying bedrock at level –40m to –90m. Both sides are on reclaimed land.

3. The Design

Stonecutters Bridge is the first cable-stayed bridge with a span over 1km for which detailed design has been completed. Particular challenges in the design have been due to the site, which is exposed to typhoon winds and the busy harbour, imposing severe restrictions on the construction operations. Also the bridge will carry traffic with a very high content of Heavy Goods Vehicles

3.1. Design Criteria

The design criteria are summarised in the Design Memorandum for Stonecutters Bridge and are based on the Structures Design Manual for Highways and Railways (SDM) issued by HyD supplemented by BS5400 and other relevant codes. However, a number of investigations have been carried out to establish site-specific design loads from wind, seismic activities and accidental ship impact.

3.1.1. Wind Loading

The structure's response to dynamic wind has dominated the design and although the SDM specifies the wind climate of Hong Kong, it has been necessary to supplement with data from other sources to determine a complete wind model as required for dynamic wind load assessments of highly flexible structures of large spatial extent. The other sources drawn upon included analysis of wind turbulence data measured at mid span of Tsing Ma, Kap Shui Mun and Ting Kau bridges; terrain model testing in 1:1500 scale of the bridge site including Tsing Yi Island and Tsing Ma/Kap Shui Mun area, as well as on-site wind turbulence measurements at the eastern end of the site.

Ocean exposure (south westerly directions) is characterised by high wind velocities and low turbulence. When the wind is approaching over mountainous/urban terrain (north westerly to south easterly directions) the wind velocity is lower but the level of turbulence is high, refer to the location plan shown in Fig. 1. The high turbulence wind has generally governed the design.

The bridge has been checked for aerodynamic instability under the wind speed thresholds corresponding to 1-minute mean wind velocities at the bridge deck level (Table 1). The critical flutter wind velocity has been confirmed using experimental methods.

Table 1 Critical wind speeds for flutter (1-minute mean)

Angle of incidence	**Without traffic** **m/sec**	**With traffic** m/sec
0°	95	50
±2.5°	75	40
±5.0°	50	25

3.1.2. Seismic Loading

A study of the risk levels for Stonecutters Bridge established three limit states, with earthquake return periods of 120 years for SLS, 2400 years for ULS and 6000 years for SILS (Structural Integrity Limit State). The bridge should behave elastically during frequently occurring or minor earthquakes (SLS) without the need for any repair. During a moderate earthquake (ULS) certain elements may undergo large deformations in the post elastic range without substantial reduction in strength, and damage level shall be minimal with repair carried out without the need for closure of the bridge. The deformation and damage of the bridge during a severe earthquake (SILS) shall not be such as to endanger emergency traffic or cause loss of structural integrity but damage might require closure of the bridge for repair. The design earthquake ground motion is represented by site-specific design response spectra (with 5% damping) determined for the three return periods.

3.1.3. Accidental loads due to Ship Impact

The tower foundations are located within reclaimed land approximately 10m from the seawalls on both sides of the Rambler Channel. Given the close proximity account has been taken in the design for impact loading induced by a ship collision with the seawall. A series of centrifuge tests have been carried out [2] to model the effect of a 155,000 tonnes container ship impacting the seawall at 6 knots. From the results of the test and correlation of the pressure measurements with representative elastic numerical models, the force exerted by the vessel impact at the front face of the bridge foundation has been determined.

3.2. Global Analysis Model

The global analysis model is established using the design tool IBDAS a general computer aided structural design and analysis system developed by COWI. IBDAS is based on 3D parametric solid modelling and provides procedures for fully integrated design and analysis of load bearing structures. Parallel independent calculations have been carried out to check the results of the global model using the commercially available software TDV.

The construction sequence is modelled as a series of construction phases, each phase consisting of activities such as: casting, building-in and removing structural parts, pre-stressing, grouting and slacking of pre-stressing tendons, stressing and slacking of stays, changing support/coupling condition and placing and removing temporary construction loads. A time indication is linked to each phase allowing calculation of time dependent effects such as creep, shrinkage and relaxation.

3.3. Construction Sequence assumed in the Design

The concrete back spans are constructed fully in advance of the cantilevering of the main span. During the cantilevering the back spans provide stability and in particular the end portal pier provides the main lateral resistance to the transverse wind load moment on the cantilever.

It is assumed that the back span deck units consisting of two longitudinal girders integral with the three cross girders are cast on temporary supports with a gap between the longitudinal girders and the pier crossheads. The full transverse prestress is applied to the cross girders prior to connecting the longitudinal girders by in situ stitches to the crossheads. When all deck units and in situ stitches are completed then the longitudinal prestress is applied. The temporary supports are released as the stay cables are tensioned and provide the permanent support to the deck.

The short length of steel deck adjacent to the tower is assumed erected on temporary scaffolding. The majority of the steel main span over the water is assumed constructed by the traditional cantilever method where prefabricated deck units are floated into position and lifted by gantry cranes on the construction front of the previously erected girders.

3.4. Design of Foundations

The foundations have been designed using an iterative process to achieve compatibility between the bridge superstructure and substructure. The pile foundations are designed to accommodate additional negative skin friction loads resulting from down-drag of the soil caused by the ongoing long-term settlement of the ground. Bearing pressures vary from 3.0MPa for moderately decomposed rock to 7.5MPa for fresh to slightly decomposed strong rock. In order to achieve optimum design of the bored pile, the base of the pile is enlarged to form a bell-out to increase the bearing capacity such that it is of similar magnitude as the structural capacity of the pile shaft.

3.5. Design of Towers

The tall circular freestanding towers with the metallic upper part provide one of the most distinctive visual features of Stonecutters Bridge and it has been of paramount importance to maintain these features in the detailed design development. Circular shape towers are known to be susceptible to vortex shedding induced vibrations and carry a risk of introducing vibrations of the stay cables due to linear resonance and/or parametric excitation. This was found to be further aggravated by the fact that the upper portion of the Reference Scheme towers is in steel with lateral tower frequencies that match the frequencies of some of the stay cables. To improve the dynamic behaviour while still maintaining the appearance, the upper tower section is designed as a composite between the stainless steel skin and the inner concrete wall. Composite action is achieved by connecting the skin to the concrete wall by means of shear studs. It is assumed that no shear stress is transferred across the horizontal splices in the skin. Distance between splices varies with stay anchorage spacing and is typically around 3300mm. The steel skin is generally assumed to resist only stresses in vertical and horizontal directions. The material stainless steel was selected for maintenance reasons. The vertical component of the stay anchorage force is transferred from the anchor box to the concrete tower wall by shear studs.

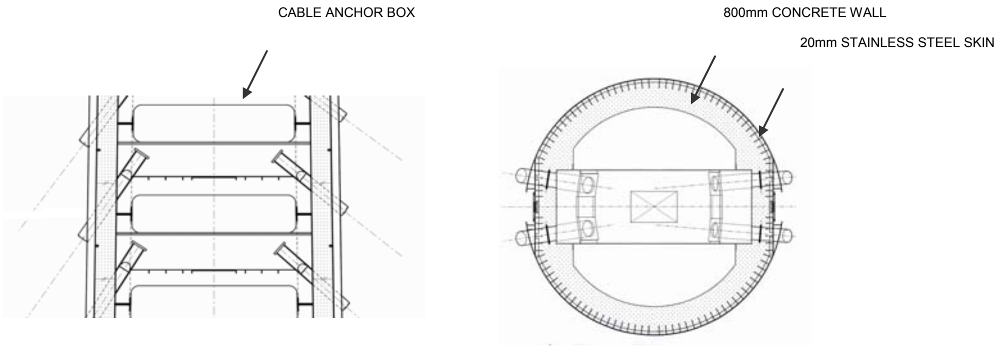


Fig. 6 Sections in Upper Tower

The lower part of the tower is designed in reinforced concrete. The longitudinal reinforcement is in general Ø50mm connected with couplers. The outer reinforcement layer consists of stainless steel bars to enhance the durability of the structure in the severe environment.

3.6. Design of Concrete Back Spans

The back spans are monolithic with the piers and the stress state due to permanent loads is therefore highly dependent on the method and sequence of constructing the various elements. The fact that the stays are connected to the outside of the deck only would, if a single large box had been used in the back spans, lead to a state of transverse bending in the box. With the chosen configuration of two longitudinal box girders connected by cross girders the result is a combination of torsion in the longitudinal boxes and bending (sagging) in the cross girders. The ratio between torsion and bending depends on the stiffness ratio of the members and therefore relatively high torsion stresses exist in the structure due to permanent loads. It is possible to make some adjustment to the distribution of forces through the construction method by building in restraint forces but due to the scale of the structure and the nature of the material, this has only been attempted to a limited degree.

The assumed construction sequence ensures the maximum efficiency of the transverse prestress as the cross girders are unrestrained during stressing. It also offers the possibility of some adjustment to the permanent torsion in the longitudinal girders. The cross girder tendons are all placed at maximum eccentricity at the bottom of the section, and in order to stress them fully prior to the deck being supported by the stay cables temporary prestress above deck level is required.

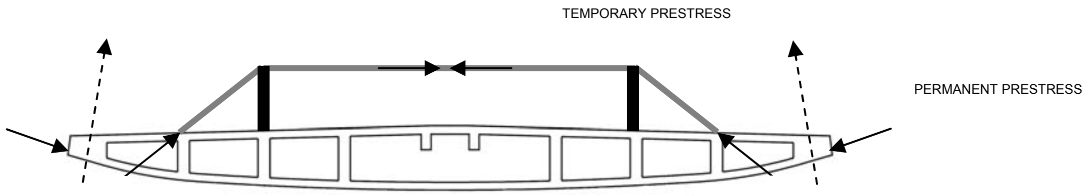


Fig. 7 Schematic Prestress of Cross Girders

When the stay cables are attached and tensioned at the deck edges, the temporary transverse prestress is released and a beneficial torsion is induced in each of the two longitudinal girders.

The longitudinal prestress consists mainly of external tendons inside the boxes with tendon deviation at the cross girder walls. The prestress demand for flexure reduces with the increasing compression towards the towers. The interface between the concrete and steel is prestressed such that the joint is in compression over the entire area.

3.7. Design of Steel Deck

The 53.5 m wide steel deck consists of twin box girders connected by cross girders at the stay anchorage points. The stay cables connect to the outside edges of the deck. Typical steel deck cross section is shown in Fig 4.

The steel box is designed with an orthotropic steel deck, the design of which is governed by fatigue loading on the bridge, leading to a deck plate thickness of 18mm with 9mm thick trough stiffeners. The distance between diaphragms is generally 3.8m, and 2.8m at the cross girders, where the stay cables are connected.

The distinct and clearly visible curved outer face of the longitudinal girder and the curved soffit of the cross girders of the Reference Scheme was evaluated to be an important aesthetic feature. Substantial section model wind tunnel testing has been carried out to verify the aerodynamic stability both for the bridge in-service and during construction as well as to determine the vortex shedding response. Vortex shedding of the bridge girder could result in vibrations of the stay cables due to excitation of the cable supports. However, introducing guide vanes will mitigate vortex shedding induced vibrations. In addition to traditional section model testing in scale 1:80, which was carried out at the Danish Maritime Institute (DMI), it was decided to perform tests in scale 1:20 to increase the Reynolds Number one order above the traditional tests. These high Reynolds number tests were conducted at the National Research Council of Canada (NRCC). During the detailed design the guide vane layout was refined based on forced motion tests on the 1:20 scale model.

The quantity of structural steel amounts to approximately 32,000 tonnes in total. For the longitudinal girders the maximum plate thickness applied is generally 40 mm. For the cross girders the maximum plate thickness is 50 mm (adjacent to the towers). The steel quantities have been governed by the typhoon wind loading, and in particular the dynamic response of the structure to turbulent wind. Steel grade S420 M and S420 ML have been specified.

3.8. Design of Stay Cables

The stay cables used in the detailed design are the prefabricated PWS type with Ø7mm galvanized wires and extruded outer HDPE sheathing. The tensile strength of the wires is 1770Mpa and allowable stress at service load is 769MPa. Stay cable outer diameters vary from 113mm (163 wires) near the towers to 192mm (499 wires) towards the end of the back spans. The longest cable is 540m long and weighs about 70 tonnes.

Wind tunnel tests in scale 1:1 have been carried out on stay cables of various diameters to confirm the drag coefficient used in the design and to investigate the effect of various surface profiles to counteract rain-wind induced vibrations.

4. Conclusion

The aesthetics of bridges are now rightly on the agenda and bridge owners the world over have understood what a powerful image a beautiful bridge structure can be. Bridge designs are therefore increasingly being procured through design competitions where aesthetic as well as technical qualities are considered and judged. The manner in which Highways Department conducted the design competition for Stonecutters Bridge ensured that the winning scheme, the Reference Scheme, would have both high technical merit and high aesthetic value. The thorough review carried out prior to the start of detailed design proved the feasibility of the design and the modifications introduced have not in any way changed the aesthetic appeal of the structure.

Bridges of the scale and in the location of Stonecutters Bridge have the opportunity of becoming icons, of becoming defining images of cities, like the Golden Gate Bridge, Sydney Harbour Bridge and Brooklyn Bridge. We believe Stonecutters has the potential to become an icon for Hong Kong.

5. Acknowledgement

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6. References

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