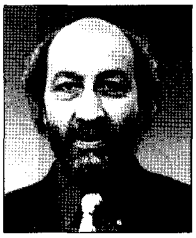
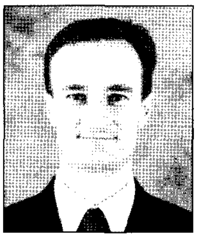
Stonecutters Bridge in Hong Kong Design, Analysis and Construction





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Stonecutters Bridge, currently under construction in Hong Kong, will form the centrepiece of the new Route 8 east-west expressway. The road will provide an additional link in the region of the new container terminal on Tsing Yi Island, as well as linking through a new tunnel to Shatin on the east side of the New Territories and through the new Nam Wan tunnel to join to the airport route on the west side of Tsing Yi.

Stonecutters Bridge is a cable-stayed bridge with a main span of 1018m, making it one of the longest in the world. The bridge catches international attention not only because of its span length, but because of the unique setting in the urban area, where it will be visible from Hong Kong Island as a backdrop to the famous harbour. The design of the bridge was adopted from the winning design of an international design competition, organised by Highways Department of Hong Kong, which elicited participation from some of

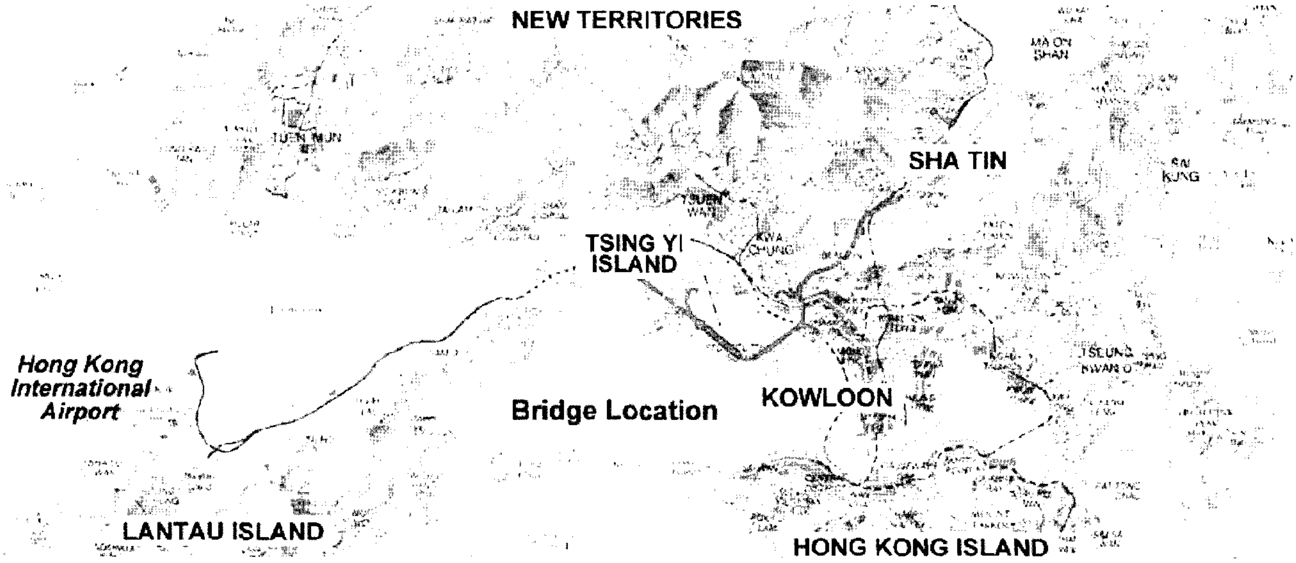

Fig.1 Location of Stonecutters Bridge

the best architectural and engineering firms in the world. Detailed design of the bridge was performed by Arup, with COWI as sub-consultant.

The competition winning scheme has single tapered cylindrical towers standing on the bridge centreline between the twin deck box girders which are interconnected with transverse members. Stay cables are arranged in a semi-fan configuration, connecting to the steel deck in the main span at 18m intervals, and to the concrete deck in the back spans at 10m intervals.

Construction of the adjacent high level approach viaducts and the Nam Wan Tunnel has been let as three separate contracts. The design for these precast segmental bridges and the tunnel was also by Arup, who have gone on to provide the site supervision team to administer the construction contracts. The alignment of this 7.6km section of the dual three lane Route 8 highway has been largely dictated by the shipping clearance requirements. Stonecutters Bridge spans the Rambler Channel at the shipping entrance to the busy Kwai Chung Container terminals. The minimum shipping clearance was chosen as 73.5m above sea level to allow not only for the largest container ships in use at the time of design, but also for those being planned for use in the future.

The construction contract for the bridge commenced in April 2004, with the Maeda-Hitachi-Yokogawa-Hsin Chong Joint Venture appointed as main contractor, and Arup supervising. Site work has been progressing since then, with the East Tower now standing 200m tall and the East Back Span concrete decks complete. On the west side the land was not available to the Contractor immediately, so construction there follows on about 4 months behind that on the east. Meanwhile fabrication of the steel deck segments and upper tower steelwork has been taking place in China, with the first units recently delivered to site. Main span closure is scheduled for the end of 2008.

The total length of the bridge is 1596m made up of a main span of 1018m and four back spans on each side, of 79.75m, 70m, 70m and 69.25m. The main span deck is in steel and the back span decks are in prestressed concrete to give a good load balance to the huge main span. The towers are formed of concrete to +175m, and of composite construction with an outer stainless steel skin to +293m and topped by a lighting feature to +298m. Stay cables are in 2 planes arranged

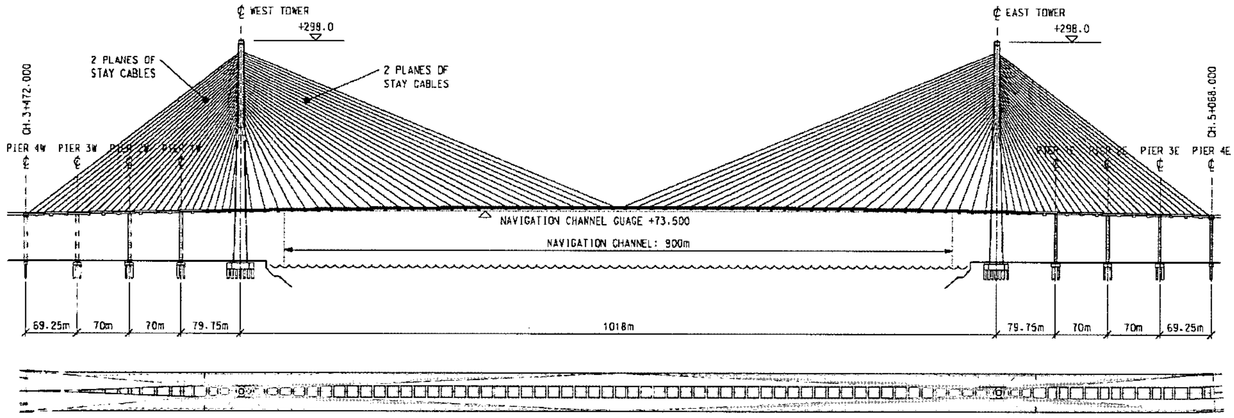

Fig. 2 Elevation and plan

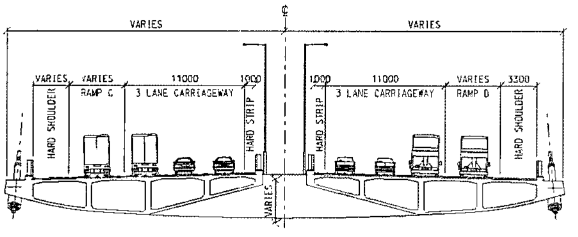

Fig. 3 Concrete deck - west back spans

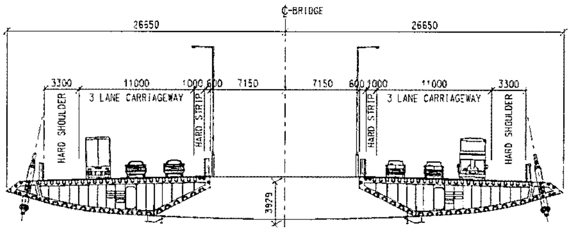

Fig. 4 Steel deck - main span

in a modified fan layout and attached to the outside edges of the deck.

The detailed design analysis of the bridge was performed using the COWI software IBDAS (Integrated Bridge Design and Analysis System). IBDAS is based on 3D parametric solid modelling and provides procedures for fully integrated design and analysis of load bearing structures. A parallel analysis was run by Arup in the commercially available software RM2000 from TDV to verify the results, and to investigate design options for the concrete back spans. The RM2000 model also forms the checking model for the Contractor's detailed erection proposals.

All computations are based on theory of elasticity and geometric non-linear analysis (2nd order analysis). Construction process modelling is carried out using a sequence of phases, each consisting of activities such as casting, building-in and removing structural parts, stressing tendons, stressing or de-tensioning stays, changing support conditions and placing/removing temporary loads. Time dependent effects such as creep, shrinkage and relaxation are considered according to Hong Kong Structures Design Manual for Highways and Railways and BS5400. A total of 110 construction phases were modelled starting with concreting of piles and pile caps and ending with the completed bridge after 120 years of service life.

The verification was based upon a two-staged analysis. The first stage involved a space frame global analysis from which sectional forces were found at critical sections. The corresponding stresses were then checked against the relevant clauses of BS5400. In the second stage, rather than using the traditional approach of selecting a limited part of the structure and making a separate detailed local model, a "semi-local" model was used. Most of the model was identical to the global 3D model, but more detailed shell modelling of selected sections was used. Analyses of a limited number of loadcases were run to investigate effects such as stresses at the connection between the longitudinal girders and the cross girders and also the shear lag effects associated with the introduction of the stay force towards the outer edge of the deck. This eliminates problems of local models where boundary conditions and loading application on the detailed model can be difficult.

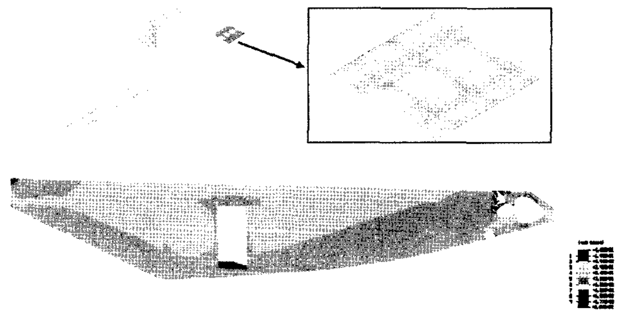

Fig. 5 Semi-local model of Stonecutters Bridge and Stress contour plot of diaphragm plate, IBDAS

Longitudinal and transverse prestress design in the concrete back spans was optimised by iterating the RM2000 analysis. Input of tendon geometry and stressing forces was controlled by spreadsheets to allow rapid updates.

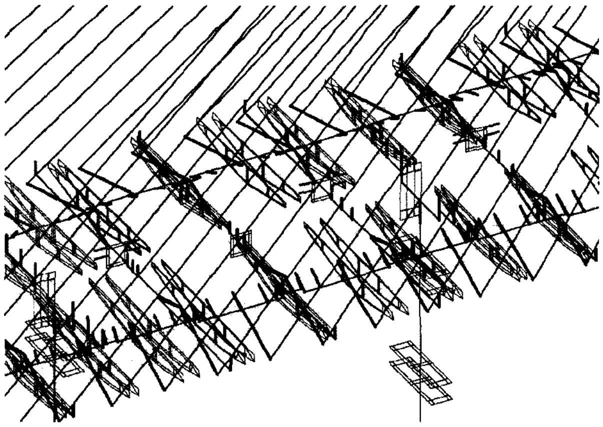

Fig. 6 Detail of Concrete Back Span, RM2000 Global Model

Hong Kong is subject to typhoons and detailed design of the structure was almost totally governed by the aggressive wind climate. From the early stages of design a thorough study of the wind from existing weather records and site-specific measurements was conducted. This resulted in the definition of a project-specific wind loading model, giving the design wind speeds and the level of turbulence.

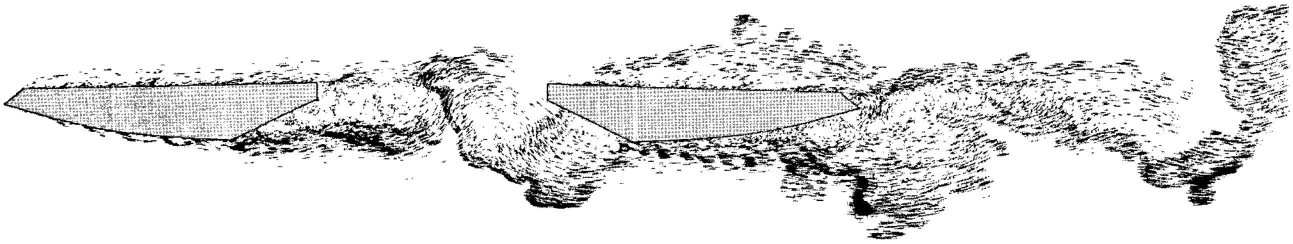

Fig. 7 Flow plot from DVMFLOW model

During the initial phases of the design, before results from wind tunnel testing were available, simulations of the aerodynamic behaviour of the bridge were carried out by means of the in-house computer program DVMFLOW. This is a two-dimensional version of the discrete vortex method programmed for simulation of flow around bluff bodies, stationary, elastically suspended or in prescribed motion. As the design progressed substantial section model wind tunnel testing were carried out to verify the aerodynamic stability and to supply refined information on the steady state wind load coefficients for the global analysis. Confirmatory 3D aeroelastic full bridge model tests at scale 1:200 have been carried out.

Load combinations with mean and buffeting wind load were governing for the design of most of the bridge. Different wind scenarios were investigated, depending on wind direction and whether or not traffic is present on the bridge. The analyses were carried out as spectral buffeting analyses based on Davenports buffeting theory. Each analysis comprised the 30 lowest global modes. Special analyses were also carried out to investigate the possibility of wind induced stay vibrations.

For seismic action, 3 limit states were investigated, each with several different support conditions resembling different liquefaction scenarios. 300 eigenfrequencies were included, up to 7.8Hz and with more than 95% of the total mass included. The CQC-method was used assuming uniform ground motion with non-synchronous motion included via settlement loads.

Additional time history analyses were made to check sudden stay rupture using a 3-step procedure: First, determination of the static force/reaction in the stay assumed to rupture. Secondly, removal of the stay and adding the reactions determined in the previous step. The stay is thus physically removed, but the structure still has an equilibrium state as if the stay was present. Finally, performing the time history analysis, where the stay reactions are instantly removed. In this way, the dynamic effects of the stay rupture are included in an efficient manner.

Another important loading scenario is that of a very large container ship accidentally impacting in the sea wall in front of one of the towers. The tower foundations are located behind the sea walls, but a ship impact would still impose significant loading onto the structure. Determining the magnitude of this potential loading was important is sizing the foundations, and a novel approach was chosen. A combination of numerical and physical modelling was adopted to maximise the benefits of each approach. A 3D finite element time-history analysis is a very powerful tool where many scenarios can be run relatively quickly and detailed results extracted. However, in order to gain confidence in the theoretical results generated in the LS-DYNA model, calibration against a physical model test was required. A 1:200 scale model was built with a typical ships bow, the sea wall and the preliminary piled foundation design. Scaling effects meant that the stress distribution would not be correctly represented. To overcome this, the model was placed inside a geotechnical centrifuge and accelerated to 200 times gravity in order to correct the scaling effect. The results from pressure sensors placed within the model could then be relied upon as the ship was pushed into the representation of the sea wall. These results were used to fine tune the finite element model so that more analysis runs and different piled foundation arrangements could be investigated and detailed results used in the design.

The resulting ship impact loading was then analysed in the global model using time history analyses with 6 impact cases investigated combining the results of

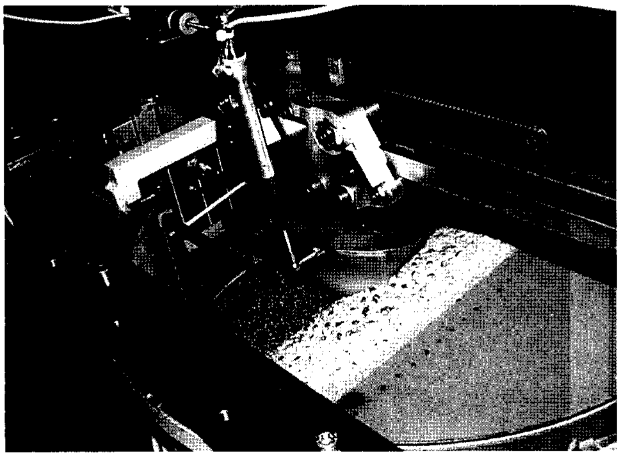

Fig. 8 Ship Impact Model in centrifuge

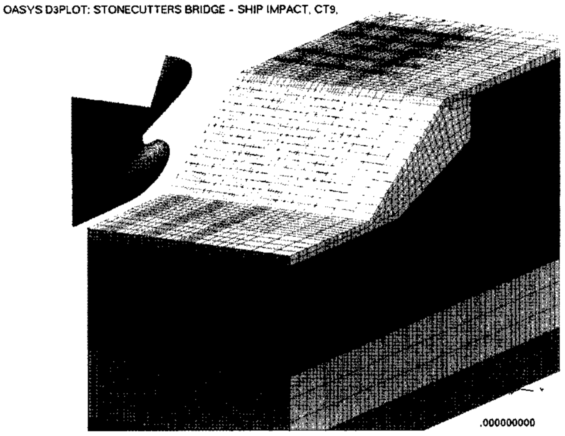

Fig. 9 3D impact simulation, LS-DYNA

time history analyses with load combinations including buffeting wind loads.

The results of all the global analyses comprised investigation of 91 basic loads and load combinations giving forces at some 800 output design sections in tabular form. Plots and figures supplying overview of the results were also provided. For each complete run of analyses 2.5 GB data were produced to be used by the design team in their calculations.

Construction of the back span concrete decks is one of the most complicated aspects for the Contractor. The slender deck requires the support of the stay cables to span between piers, but these are not installed until later in construction when the corresponding main span cables are in place to support the deck cantilever as it extends over the channel. A huge temporary falsework system is required during the construction phase to enable the in-situ deck to be cast and this remains in place until the stays are installed.

Fig. 10 Back Span Falsework - East Side

A large quantity of temporary prestressing is required prior to the stay cable installation. Each cross girder in the back spans has prestressing spanning across the deck between stay cables in the permanent condition. But temporary bowstring prestress is required to add top slab compression and twist to the main girders, mimicking the effect the stays will have later.

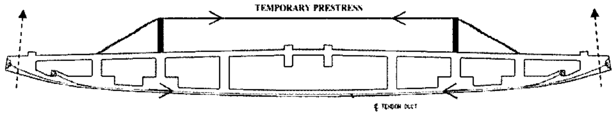

Fig. 11 Schematic prestress of cross girders

The climbform system used for lower tower construction had to be flexible enough to deal with the tapering section shape which changes from an elongated circle 18m by 24m at ground level to a true circle of diameter 14m at deck level and on to a 11m diameter circle at +175m height.

Upper tower steelwork includes the central steel anchor box, providing the tying resistance between the main span cables and back span ones, and the outer 20mm thick stainless steel skin. The outer skin material was chosen to minimise the maintenance requirements for the areas which are very difficult to access. Geometry control in fabrication is one of the most important aspects to ensure that a vertical alignment is maintained when the segments are erected on site. All anchor boxes and skins are match fabricated and trial assembled in stacks of 3 to ensure control.

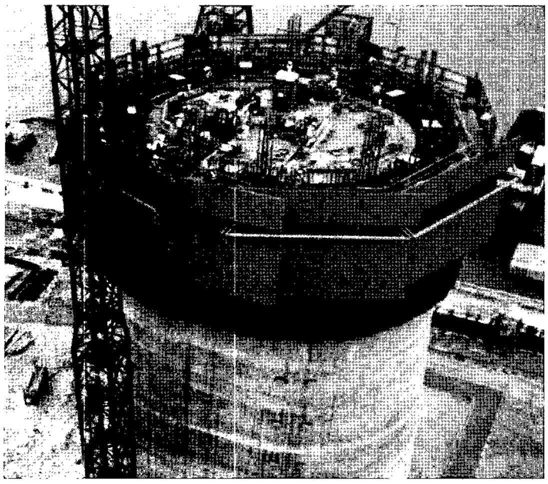

Fig. 12 Lower Tower Construction

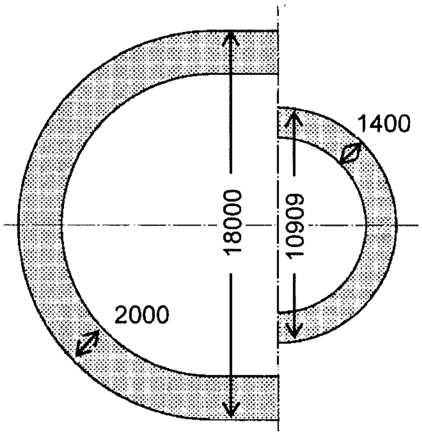

Fig. 13 Lower Tower Shape at base and +175m

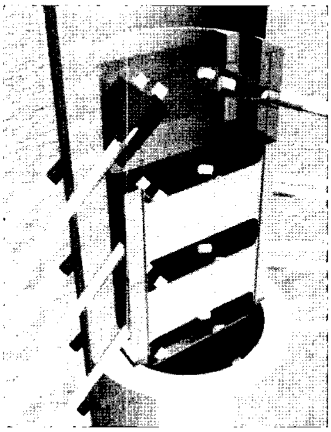

Fig. 14 Upper Tower - cut away

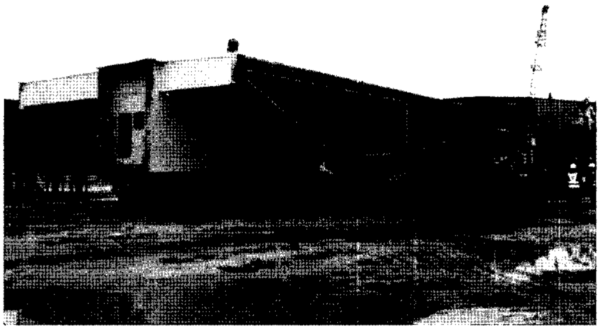

Fig. 15 Steel Deck Assembly - First unit complete

Steel deck segments started arriving from China at the end of 2006. In a similar way to the tower steelwork, match fabrication and accurate geometry control are vital in order to assure the correct alignment of the deck when erected. The 88m lengths of deck around the towers will be lifted into place in a 4000T heavy lift scheme. After that main span erection will take place with 18m long units lifted from a dynamically positioned barge. Minimum

Fig. 16 Stonecutters Bridge - a new icon for Hong Kong in 2009

disruption to the shipping traffic is key to ensuring a successful outcome for the project.

The appearance of bridges is becoming increasingly important for bridge owners and the conceptual design is often selected through a design competition. The increased focus on innovative and aesthetically pleasing structures has led to beautiful bridges but also to structures which are technically more challenging to design, build, operate and maintain. Stonecutters Bridge is an example of such a bridge, where complex computer modeling and analysis was needed in the detailed design to thoroughly investigate potential loading scenarios. The bridge will make a dramatic architectural statement whilst at the same time pushing the boundaries of design and construction.