Particular Design Features for a Long Span Cable-Stayed Bridge over the Harbour of Port Louis, Mauritius

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ABSTRACT: Specific requirements from the contractor as well as local conditions have demanded very particular design features for the Port Luis Harbour Bridge in Mauritius. The conceptual design of the bridge has been carried out in the context of a competition for a large PPP traffic infrastructure project. The special requirements are described and the corresponding design solutions are presented. Main features are the design as a long span concrete bridge, the integral approach without joints and bearings, steel inserts in the pylon, the integral foundation as well as a pylon top restaurant.

1 INTRODUCTION

In the context of a large PPP traffic infrastructure project in the area of Port Louis on the isle of Mauritius a bridge over the Harbour basin of Port Louis has been designed. The bridge connects the existing road network on the north side of the harbour to the existing road network on the south side and acts thus as a bypass for the city. The bridge features a free main span of 500 m spanning from shore to shore.

For the new Harbour Bridge a cable-stayed bridge with a single-layer cable harp has been chosen as structural system. The pylon is diamond shaped. The girders of the approach bridges, as well as the main span, are single section reinforced and post-tensioned concrete box girder. The approach bridges are designed as continuous girder.

Figure 1: Rendering of the Bridge

As the owner intends the bridge to be valued as a landmark and tourist attraction, a restaurant has been designed on top of one of the pylons. In cooperation with an architect this additional element has been developed. After initial scepticism adding an additional element to the elegant bridge the whole team was finally convinced of the approach and also structural analysis showed that the restaurant on top of a pylon 'fits' pretty well to a cable-stayed bridge.

Due to special requirements from the contractor as well as local conditions there are several particular design features that have been implemented in the bridge. This is namely the design as large span concrete bridge, the integral approach without joints and bearings, steel inserts in the pylon, the integral foundation as well as the aforementioned pylon top restaurant.

2 DESIGN REQUIREMENTS

2.1 *Road Cross-Section*

The requirements for number and width of traffic lanes of the road cross section are given by the local road authority RDA. Both directional carriageways are situated on one bridge girder. There is a safety lane for both directions, but no footpath. The two carriageways are separated by a standard concrete median barrier and concrete parapets are provided to both sides.

The widths of the lanes are conforming with RDA requirements as well as with the South African codes for traffic design:

- Traffic lane. 3.75m
- Safety lane and outer margin to parapet.1.5 m
- Inner margin to parapet: 1 m

Due to the specific structural design of the bridge there are two different arrangements of the directional lanes. The standard section has a spacing of 1 m between the two carriageways. The section where there is a cable features a width of 2 m to allow the anchorage of the cable and to provide a safety margin for potential impact on the cable from traffic.

2.2 *Architectural Design*

The analysis of the site has shown that site and technical requirements for the new Harbour Bridge are pretty complex. There is a large variety of existing zones interacting with each other; urban quarters, industrial districts, maritime environment, sea and mountains. Thus, the main architectural approach is to create a link between these domains with a retaining and sober structure (see figure 2).

The bridge structure acts as a link between:

- north and south rim
- sea and town
- scenic landscape and modern industry
- modern urban style and maritime environment
- flat land and high mountains

The structure should thus appear as light and transparent as possible in order to avoid any separating effect between Port Louis and the open sea. It should be a self-retaining functional structure that will not dominate the environment by avoiding that an additional strange element is added to an already quite in-homogeneous environment. However, the bridge should be representative and act as a landmark.

Figure 2: A non-homogeneous, multi-aspect environment for the new Harbour Bridge

2.3 *Arrangement of the Bridge*

The bridge (total length 1584 m) is subdivided into the main bridge (1020 m) and a north (398 m) and south (166 m) approach bridge. The main bridge has a 490 m long main span and two back spans (2 x 265m) on both sides. The main bridge and the approach bridges are separated by expansion joints. The approach bridges are inclined at a gradient of up to 7.5 % and act thus as ramps to reach the height of the main bridge crossing the navigation channel of 50 m height. The bridge is designed to appear as one bridge even though, from a structural point of view it is subdivided in separate elements.

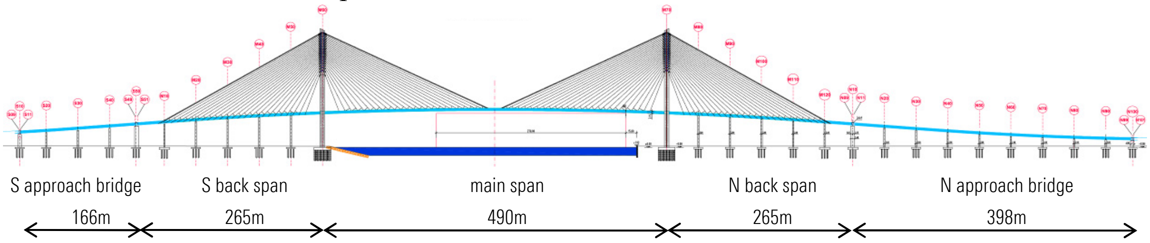

Figure 3: Arrangement of the bridge

3 LARGE SPAN CONCRETE BRIDGE

Due to the specific characteristics of the bridge structure and the lack of steel construction contractors on the isle of Mauritius as well as requirements from the PPP contractor, the bridge deck has been designed as a light concrete box girder. This choice leads to a robust and durable bridge girder. Compared to steel or steel composite girders commonly applied in mid-span of cable-stayed bridges, the concrete box girder does not entail corrosion problems in maritime areas. A steel girder has a very high maintenance for regular renewal of corrosion protection.

The concrete box girder is heavier than typical steel or composite cross sections. Thus the bridge system is subject to higher loads by its dead weight, but this presents a considerable advantage in view of the structure's sensitivity to wind. Mauritius is situated in a cyclone area. Light bridge decks could cause vibrations induced by wind. A heavy and stiff cross section such as used in this project counteracts this effect.

The section of the main span is a 22.95 m wide concrete box girder optimized for cable-stayed bridges (see figure 4). The thickness of the web, deck and bottom is reduced to a minimum. Internal steel struts distribute loads from the outside to the central suspension point. The concrete box girder distributes torsional forces in longitudinal direction to the pylons. This smart combination of materials leads to a very light and efficient structure for a concrete cross section.

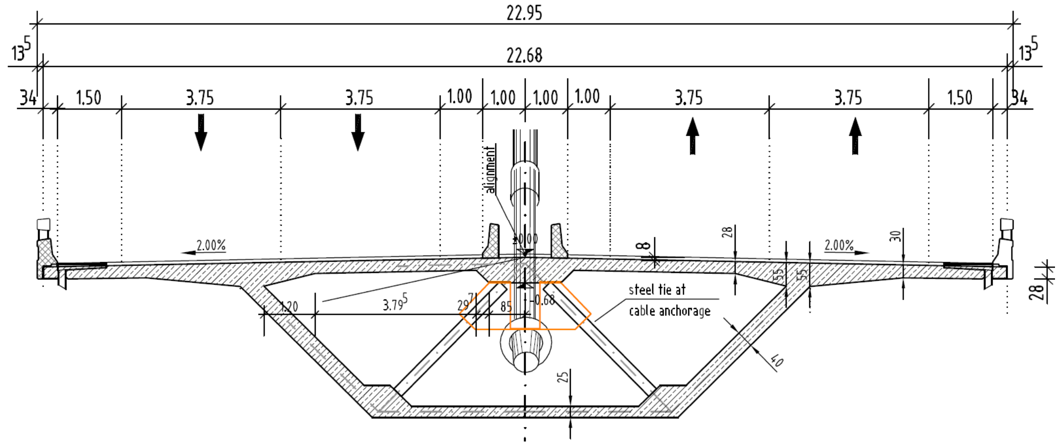

Figure 4: Standard section of the main span of the cable-stayed bridge

The standard section of the back span of the cable-stayed bridge is designed as standard concrete box girder (see figure 5). There is both longitudinal and transversal post-tensioning. In the centre between the lanes there is space of 1m width to allow anchorage of the cables. There is a specific configuration of cross girders in the back span to enable transfer of loads from both sides to the centre where the cable is attached at the bottom of the girder.

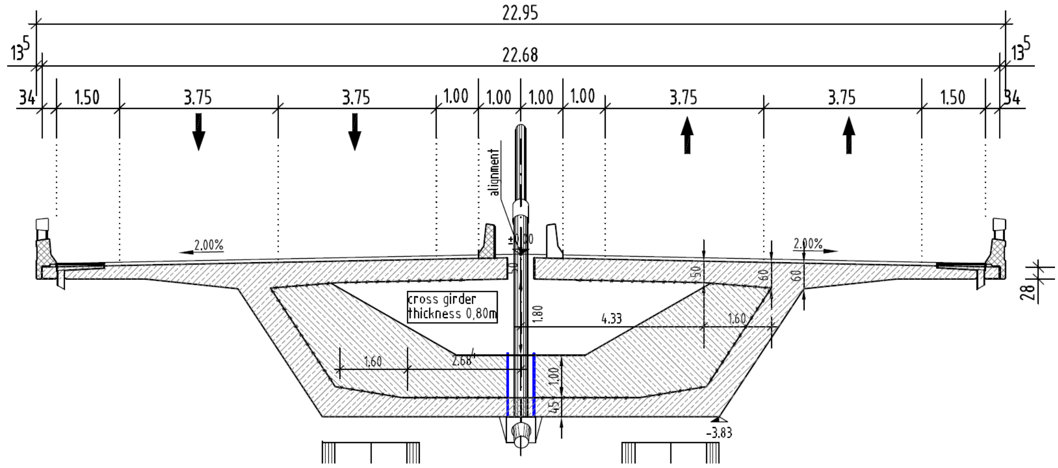

Figure 5: Standard section of the back span of the cable-stayed bridges

The approach bridges are designed as standard concrete box girders (see figure 6). The bridge deck has a total width of 21.95 m. The thickness of the edge cantilevers reduces from web to parapet to reduce the dead load and the webs are inclined to optimise the box girder. There is both longitudinal and transversal post-tensioning.

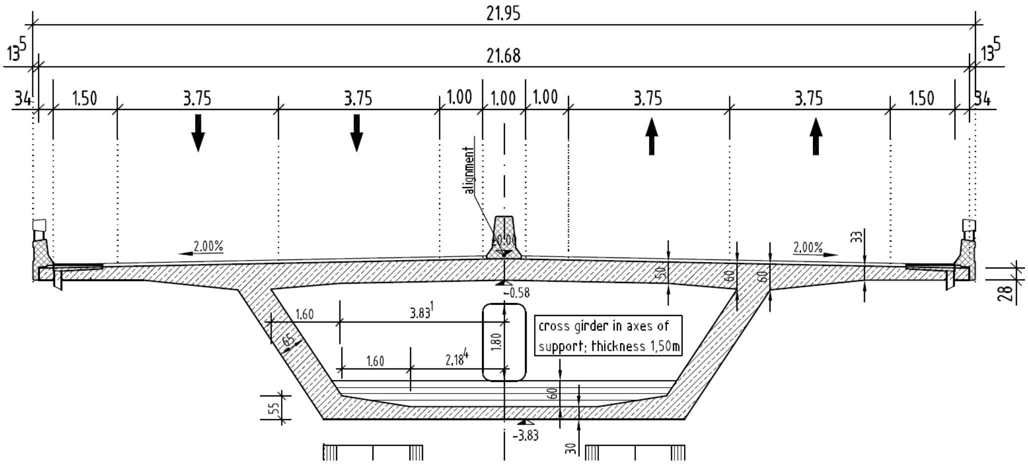

Figure 6: Standard section of the north and south approach bridges

4 INTEGRAL BRIDGE STRUCTURE

The main bridge girder is connected rigidly to the pylon, resulting in a very robust and durable integral framing structure. Time-dependent constraint deformations, such as temperature or creep and shrinkage, can be distributed by deformations of the 50 m long pylon legs. This structural type eliminates very difficult and expensive, maintenance-intensive bearings between bridge girder and pylon. The chosen solution is quasi maintenance free and highly sustainable leading to low live cycle costs.

By being rigidly connected the two pylons act as horizontal fix points for the girder. Thus, the virtual fix point of the bridge is situated in the middle of the main span. The first piers on both sides are also directly connected to the bridge. All other piers are longitudinally free of deformation and restrained in transversal direction to use all piers during transversely load bearing.

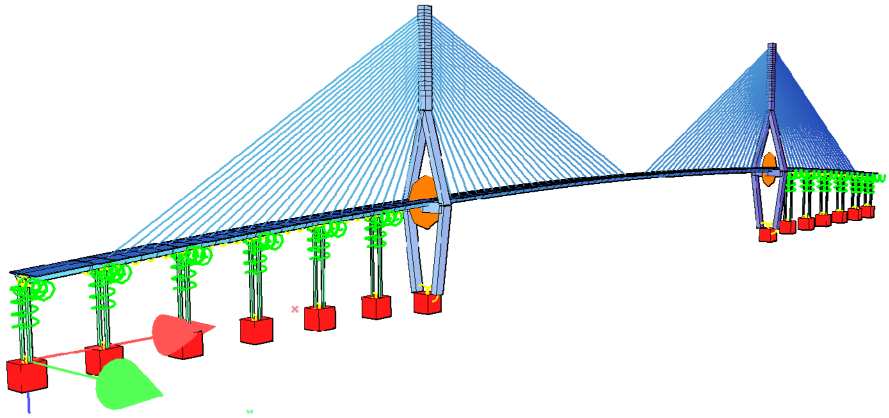

Figure 7: Structural Model of the integral bridge structure using SOFiSTiK.

5 CONCRETE PYLON WITH STEEL INSERTS FOR CABLE ANCHORAGE

The Pylon is designed in diamond shape, offering a very good combination of high stiffness in the transverse direction and a small contact surface at the pylon foot compared to an A-shaped pylon. The pylon is divided in 3 sections: the two-piece pylon base (pylon legs), the two-piece centre part and the pylon top in which the cables are anchored. In the bend between base and centre part, a horizontal beam is designed at height of the carriageway. At this beam the carriageway girder of the bridge is connected rigidly to the pylon (see figure 8).

In the cross beam, loads from the upper part of the pylon are deviated and transferred to the lower part. In addition horizontal and vertical forces from the bridge girder are transferred via the beam to the pylon. In order to take the deviation forces in this highly loaded element, the cross beam is post-tensioned.

In the upper part of the pylon, cables are anchored. A modular system made of prefabricated steel components is developed. These steel components consist of two bulkheads and anchor plates at both ends. On both sides the necessary infrastructure for further development is already integrated into the components (ladders, platforms, safety devices). Horizontal forces of opposite anchoring heads are coupled by two bulkheads. Vertical forces are distributed into the concrete by shear studs on both sides. To erect the pylon, the components are placed on the already concreted part and cast with the next concreting section.

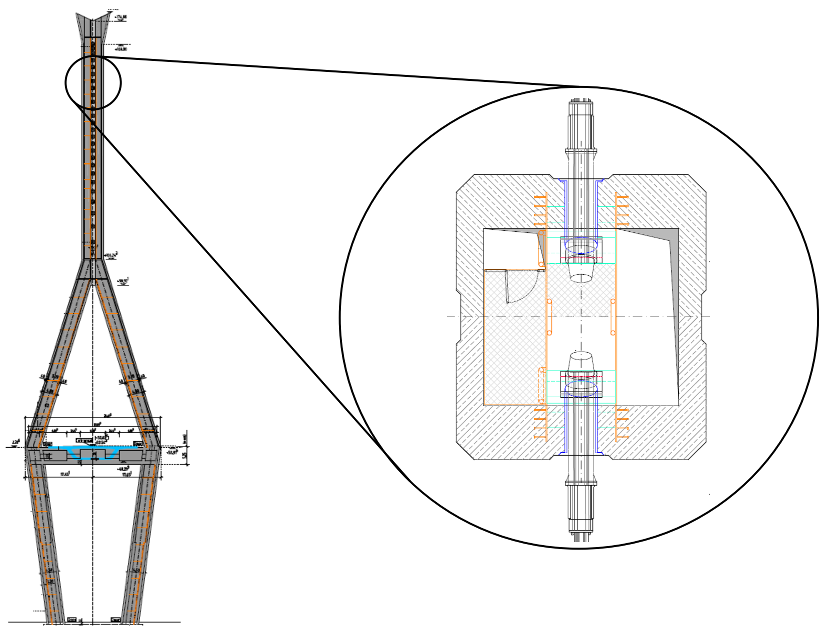

Figure 8: Diamond shaped pylon and cross section of pylon tip with inserts for cable anchorage

6 POST-TENSIONING

In addition to the cables, post-tensioning is required locally. Post-tensioning is provided in a straight line in the bottom and the top cord. Zones where post-tensioning is required are:

- In the middle of the main span to compensate tension due to the horizontal forces of the cables.
- Next to the pylon, as there is no cable support and constraint stresses have to be considered
- At the very end of the main bridge where there is no cable support.
- At the piers' location to avoid local stress concentration.

Furthermore post-tensioning is required for the free cantilevering along the whole main span.

7 INTEGRAL FOUNDATION

The foundation of the pylons is situated in direct proximity to the shore line and in consequence groundwater level is just slightly below ground level. Therefore an integral foundation is implemented combining the temporary construction pit with a traditional pile foundation. In this way both elements contribute permanently at load bearing in final stage. In the present case of the pylon foundation, a watertight, intersecting bored pile wall is built, implemented as two intersecting circles. The wall supports itself due to vault effect. Stiffeners and back anchors are not required. The stiffening of the intersecting edge between the circles is also provided by a bored pile wall. In addition to the piles of the pile wall, traditional bored piles are planned for load distribution (see figure 9).

Within the bored pile wall, the construction pit can be excavated. To seal the pit lying directly by the sea, an underwater concrete bottom slab is cast. At level of the bottom slab the inner reinforcement for the pile wall is uncovered and connecting reinforcement is welded. The traditional piles on the inside are broken back and prepared for being cast into the pile cap. The pile caps are concreted and form a monolithic foundation in which the internal piles and the piles of the bored pile wall contribute together for load bearing of the pylons.

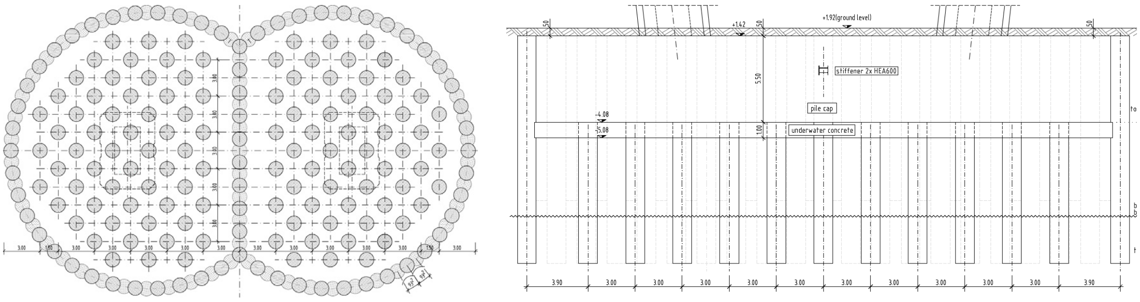

Figure 9: Pile arrangement and cross section of pylon foundation

8 CALCULATION PROCESS

In the structural analysis are considered the final stage as well as all construction stages. This enables holistic assessment of pretension of the cables. The deformed geometry of the superstructure is taken into consideration precisely. For the calculation of internal forces the construction process of the whole structure is taken into consideration. The superstructure, the pylons and piles are modelled as beams. The stiffness of the superstructure is condensed to one beam. The bending and torsional inertia moments are exactly defined. Calculations are carried out using SOFiSTiK calculation software.

The so called 'form finding' is the process where self-weight is introduced in order to determine the initial cable pre-tensioning forces to achieve equilibrium of forces for the non-deformed system at the "target geometry". The geometry of the bridge deck structure is set using an iterative process during the form finding process.

Pre-tensioning forces of the cables are chosen in a way that an optimal course of moments and pylon deformations is achieved at the moment of start of service.

In the present case of a concrete cross section for the mid span section cable spacing has to be chosen rather small. This leads to a quasi continuously bedded beam, which in context of a rather stiff concrete girder leads to high sensitivity in the iteration process. Very little modification of strain in the cables results in high increment of stress. The standard equation solver of SOFiSTiK lead in this case to instability. Thus iteration had to be carried out partly manually.

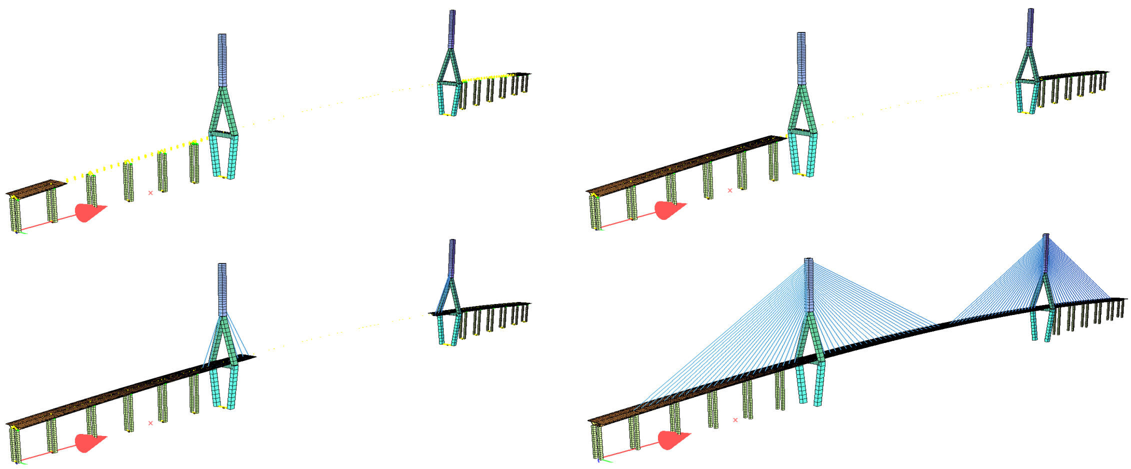

Figure 10: Selected construction stages

In the structural analysis, the whole construction process in accordance with the construction schedule is taken into consideration. Using the construction stage manager (CSM) from SOFiSTiK, construction stages are modelled. For each construction stage deformation and internal forces are calculated and taken from one to the next calculation step in order to obtain the induced constraint stresses and strain in final stage.

Internal forces for dimensioning at ultimate limit state include the stresses from the construction stages and result from multiplying characteristic internal forces with the partial safety coefficients. All structural elements are dimensioned using the programme AQB from SOFiSTiK.

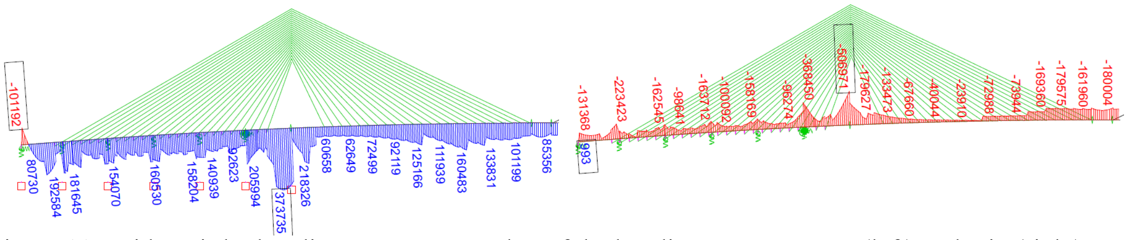

Figure 11: Bridge girder bending moment. Envelop of the bending moment: max (left) and min (right)

9 PYLON TOP RESTAURANT

As the owner intends the bridge to be valued as a landmark and tourist attraction a restaurant has been designed on top of one of the pylons. In cooperation with an architect this additional element has been added. Located directly in front of the Port Louis city where Caudan Waterfront meets the harbour area, the Mauritius Harbour Bridge and the so called Sky Diamond restaurant will be visible to ships and yachts anchored in the harbour, air traffic as well as motorists and pedestrians in the city, making it a significant landmark for Port Louis and greater Mauritius.

After initial scepticism adding an additional element to the elegant bridge the whole team was finally convinced of the approach. Also structural analysis showed that the restaurant on top of a pylon 'fits' pretty well to the cable-stayed bridge. Due to the very high normal force in the pylons caused by the deviation of the cables and the stabilising effect of the cable harp in one direction and the diamond shaped pylon in the other, there is quasi no influence on dimensioning from the loads of the restaurant.


Figure 12: Rendering of the Bridge with Sky Diamond Restaurant