Design of aesthetically pleasing bridges for the Dubai Marina

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ABSTRACT

Dubai Marina is a 700-acre development and promises to be a city within a city and marks one of Gulf's biggest real estate development projects. The development vision is for over 40 million square feet of building area. A major infrastructure program is currently under way and as part of the new road network four new bridges, with the main spans of up to 126m, are being built. The bridges have an overall width of 28m and will connect the island Marina to the existing road network over a 3.5km long featured canal. The client's desire was for the bridges to be of high aesthetic and engineering quality. Hyder Consulting's specialist bridge design team spent a considerable time developing their concept with the project architect. The most prominent feature of the structure is its soffit which comprises a crescent shaped curved and dished profile. The solution adopted for the bridge design is essentially a three span continuous post tensioned box girder structure but to provide a visual effect of a single span structure the two back spans "disappear" inside the abutment structures. The concept of a multi span box girder appears simple but the geometric requirements of a structure increasing in cross section not only in depth but also in width of the box posed serious challenges to the design team. The project was delivered successfully to a very tight time scale taking local environmental conditions into account while designing the structure to British Standards.

1 INTRODUCTION

Dubai is a city experiencing phenomenal growth. Recent developments in the city have witnessed the change of the country's economy from its traditional reliance on oil production to the tourism and retail industries. Dubai Marina is one of the development projects that will spearhead these changes.

The Dubai Marina Land Development project involves the construction of four bridges to link the Development to the Sheikh Zayed Road on the existing road network. Sheikh Zayed Road is the main road that connects the emirates of Dubai and Abu Dhabi in UAE. The four structures will bridge at various locations of the Development, as shown in Figure 1, over an existing "man made" canal that provides access to shipping vessels within the development.

The showpiece bridge structures have a main span of 126m. The deck width is 28m which comprises two traffic lanes and a 3.5 metre-wide walkway in each direction. Hyder Consulting's specialist bridge design team, in conjunction with the project architect, successfully developed a design which meets the client's desire for structures that are sleek, slender and elegant, ahead of time, and within budget.



Figure 1: Location Plan of the Dubai Marina and the Bridges

2 PROJECT REQUIREMENTS AND CONCEPT

The design of the bridge, as required by the client, complies with the following project specific criteria (1):

- The appearance of the bridge shall be slender and elegant. The appearance shall also be sympathetic to the urban design principles of the surrounding development.
- The navigational clearance envelope shall be 40m wide by 6.5m high from a Mean High Water level and shall be located centrally in the canal.
- A 15m wide promenade with provision for emergency vehicle access shall be provided at each side of the canal under the bridge.
- The bridge is preferred to be single span with no obstruction in the existing canal and the promenade.

A host of structural forms that are appropriate for the long bridges were considered. These ranged from cable stayed structure with single or dual mast, steel box girder and low rise structure with single or multiple span box girders. The cable-stayed option was abandoned to avoid high mast projecting above the canal skyline and obstruction of the surrounding medium-to-high-rise building development. The steel solution also suffered from aesthetic and environmental requirements.

The bridge design team spent a considerable amount of time with the project architect in developing a slender structure with varying depth. The most prominent feature of the structure is its soffit which comprises a crescent shaped curved and dished profile, reminiscent of the symbolic crescent that adorns the national regalia of many Islamic lands. The frontal plane, or the side elevation of the bridge, maintains a uniform sloping surface.

3 DESIGN SOLUTION

The challenge was finding an engineering solution that was structurally efficient while providing the aesthetic appearance.





Figure 2: Bridge General Arrangement

After careful consideration of many alternatives and combinations of different materials and support configurations, the design team chose the internally post-tensioned multi-cell concrete box girder for the bridge superstructure. The box girder adopted is primarily a three-span continuous beam. The main span of the beam is exposed while the two short back spans 'disappear' inside the abutment structures at either side of the canal as shown in Figure 2.

This solution provided the visual effect of a single span structure but offers the structural benefits of a continuous span structure. The main span has a cellular cross section while the back spans are essentially solid. Prestressing tendons together with steel reinforcement provide the strength of the box girder.

The main span, with its short but heavy back spans, acts predominantly as twin cantilevers meeting at its centre. This structural action permits a very slender structural thickness at mid-span.

4 DESIGN STANDARDS AND DESIGN CRITERIA

The following design codes and standards were used in the design of the Marina bridges:

- BS 5400 Steel, Concrete and Composite Bridges: Part 4 Code of practice for design of concrete bridges (2).
- BD37/01 Loads for Highway Bridges (3).
- BS 5400 Steel, Concrete and Composite Bridges: Part 9 Code of practice for design of bridges bearings (4).

Apart from the technical criteria included in the various standards, the bridge was designed for the following project design criteria (5):

- The bridge shall have a design life of 120 years.
- The design was to take account of the local environmental conditions.
- The design speed on the bridge shall be 60kph.
- Design traffic loading on the bridge shall be 45 units of HB loading in accordance with BD37/01.

5 FOUNDATION

The foundation of the bridges comprises of bored piles founded on the underlying rock layer. One of the key foundation design considerations for bridges of this size is the issue of settlement of the foundation. This issue is particularly important for the Marina bridges because of the configuration and the relative stiffness of the bridge deck. A small differential in settlement between the supports may lead to a significant re-distribution of forces in the deck. This could have resulted in a significant amount of additional reinforcement and prestressing tendons required to cover the force induced by the likely differential settlements. The behaviour requires a thorough understanding of the soil structure interaction of the foundation system. Hyder Consulting's design team carried out a detailed pile load distribution analysis using specialised geotechnical analysis software. A parallel pile group analysis was also undertaken using a structural analysis program. The results obtained from the two analyses were combined to arrive at a most likely settlement criteria.

The combined results of these analyses enabled the design team to select a less conservative criterion on the possible differential settlement on the abutments. Throughout the development phase for the bridge foundation, the design team worked closely with the geotechnical sub-consultant to gain advantage of their local knowledge of the site.

6 SUPERSTRUCTURE

The box girder deck profile was selected by considering the physical constraints, architectural requirement and the structural requirement. The deck is primarily a five cell box girder but in the 40m of the middle section of the span, the number of cells is reduced to three cells due to the profile of the deck.

The depth of the box girder varies from just over 5m at the abutment to 2.1m at the mid-span. With a clear distance of 126.4m between the abutments, these dimensions provide the slenderness effect sought by the client.

The post tensioning consists of 138 tendons of 37-strand cable with 7350kN jacking force. Internal tendons are used to minimise the effect of corrosion. Out of 54 top slab tendons, 38 are anchored in the solid back span at each end whilst the rest of the tendons are anchored in the top slab blisters provided in the back span cells. All the top slab tendons are terminated before the mid-span and anchored into the non-stressing top slab blisters. All 30 bottom slab tendons are anchored in the bottom slab blisters.

A total of 32 pot bearings, 8 bearings at each support, were used for each bridge, with vertical load capacity for some of these bearings reaching 21,000kN. Due to the high load carrying capacity of the bearing, the design team worked closely with the bearing supplier (6) in detailing the reinforcement around the bearings.

The cells in the box girder are large enough to walk through beside the blisters. Access to the central cell is from manholes in the median. Access to the other cells from the central cell is through access openings provided in the internal webs.

7 DECK ANALYSIS AND DESIGN

While the concept of a multiple span post-tensioned box girder is simple, the geometric requirements presented a challenge to the structural analysis and design of the girder. The cross section of the box was continuously varying. Figure 3 shows how the cross section of the box girder changed from mid-span of the bridge toward the abutments.

The analysis of the bridge deck was undertaken with the following approach:

- Longitudinal effects were analysed using a combination of a twodimensional line model and a grillage model.
- Transverse effects and local effects were analysed using a finite element model.

An important aspect in developing the detailed design of the bridges is the repetition of the design for four bridges. This means that any inefficiency in the analysis, design or documentation will be multiplied four times.

While the same structural form will be adopted for the four bridges, the span lengths at the bridge locations are different, varying from 113m to 126m.



Figure 3: Bridge Cross-Sections Mid-span to Pier

Also, the approach road geometry and ground levels at the bridge sites are slightly different. The analysis, design and documentation of the bridge needs to be rigorous enough to prevent the accumulated conservativeness but flexible enough for easy modifications to incorporate the variation of individual bridge site conditions.

Hyder Consulting's design team recognised the significance of these considerations at the early stage of the design development and devised the methodology for analysis, design and documentation to specifically address these considerations. The success of this approach is evidenced by our timely delivery of a cost effective design for the development project.

8 LOCAL EFFECTS

Another key consideration in the design of the bridge deck was the local effects on certain parts of the deck structure. These refer to locations where there was a high concentration of loading or areas where the loading distribution needed to be considered in greater detail. Two examples are the anchorage at the end of the post-tensioning tendons and the deck diaphragm, which is located over the bridge bearings.

The dispersion of the prestressing force from the anchorage plate through diaphragm and blisters was carried out using strut-and-tie model. The models related to:

- The transfer of load in three dimension to the adjacent web and flange.
- Corbel action of the force.
- Frame action of the anchorage force.

The design team compiled a three-dimensional finite element model for the deck; front abutment diaphragm and blister anchorage. The finite element analysis gave a detailed insight into the stress distribution prior to cracking and identified critical regions and local tensile stress zones. The modelling was performed with the Finite Element Program STRAND (7).

The deck was modelled using 4-Node quadrilateral shell elements to understand the transverse and torsional behaviour of the deck. Figure 4 shows the finite element model of the deck and the stress concentration.



Figure 4: Finite Element Model of the Deck

A linear elastic, three-dimensional, eight-node brick finite element was used to model the blister anchorage and front abutment diaphragm. The diaphragm finite element model gave an insight into the local tension areas, stress concentrations and dispersion of the bearing force. This understanding has helped the design team to reduce the reinforcement quantity in the diaphragm. Figure 5 shows the stress concentrations in the diaphragm.



Figure 5: Stress Concentration at Diaphragm

Initially the blister anchorage design was carried out with the strut-and-tie model as detailed in VSL REPORT SERIES (8). The initial design resulted in a heavy reinforcement in the blister due to the high jacking force. It was rationalized that without increasing the dimensions of the blister, detailing and constructing the blister would be impossible. Due to the limited cell space, increasing the blister dimensions would have virtually closed the passage through the cells. In order to improve the design and to verify the flow of forces in the blister and the surroundings, the design team decided to use finite element modelling. The finite element modelling has helped to reduce the amount of reinforcement required in the blister. Figure 6 shows the stress flow in the blister anchorage and the surroundings.



Figure 6: Stress Flow at Blister Anchorage

9 FAST-TRACKING OF DESIGN DELIVERY

During the design development there was a strong request from our client in UAE to advance the tendering of the bridges. To address the client's needs Hyder Consulting sub-divided the design by bridges and elements into packages. The design of these packages was progressively released as they reached the final design stages. This arrangement successfully brought forward the scheduled commencement of construction by three weeks.

One of the contributing factors to the success of the fast-tracked design delivery was the recognition of the local time and calendar. The time difference and working days meant that the Australian office and the Dubai office had only 12 office-hours in common each week. Also the local holidays had to be taken into account - for Dubai it was the two-week break for Ramadan and the Pilgrimage. For Australia it was the Christmas and Easter holidays.

The design delivery program was carefully planned to incorporate these to ensure the most efficient and effective flow of information.

10 CONCLUSION

The successful and timely delivery of the design to the client has demonstrated that with bridge engineers working closely with the architects it is possible to develop a solution for a structure which not only meets the structural requirements but also fulfils the aesthetic demands of the client to achieve a sleek, slender and elegant bridge.

11 REFERENCES

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