The Optimal Design Scheme of The Arch Bridge of The Double Happiness Island Based on Numerical Analysis

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Abstract. The arch bridge of The Double Happiness Island of Zhangzhou is initially designed as a through steel box girder arch structure. The span layout of the bridge is 115m, the full width of the bridge is 23.3m, the arch rib is steel box section, and the main beam is steel box girder. In this paper, through the finite element analysis and calculation, the calculation results are compared with the national standards of the industry, and the optimized design scheme is proposed for the preliminary design of the bridge, so as to implement the construction drawing design and provide reference for similar projects.

1. Project Overview
The Double Happiness Island project is situated at Zhangzhou Development Zone in the South Bank of Xiamen Bay. It is the first artificial island project as profit-oriented usage of ocean approved by the State Council of China. The project, in the shape of a circle by "double dolphins" and with a radius of 840 meters, has a total area of 221.67 hectares, including a land area of 182.30 hectares and waterside area of 11.7 hectares. The total investment in island construction and municipal supporting facilities is about 3.5 billion yuan.

The arch bridge is located at the South Ring Road of Double Happiness Island and its plane position is shown in Figure 1. Based on the overall design concept of "green ecology", the main shape of the bridge is like a bird with open wings about to soar from the water surface, which is modern, concise and generous. It gives people natural and ecological feelings and blend in perfectly with the surroundings. In terms of visual effects, white color renders the bridge's unique qualities of lightness and elegance, and the overall design presents a unified, harmonious and symmetrical beauty to meet the different needs of practicability, appreciation, artistry, and knowledge. The whole bridge has an outstanding visual effect, perfectly integrates form aesthetics with structure mechanics, and is the source to display the natural environment and drive the regional economic development.
The bridge is a half-through steel box girder structure, with the bridge span arrangement of 57.5m+57.5m = 115m and its full width of 23.3 m. The arch rib has a cross section of steel box with the height of 1.8 m and width of 1.5m and is consolidated with the concrete central pier. The bridge pier is a reinforced concrete structure, with the size of 2.5x2.0m and connects the drill pouring pile foundation where D=1.8m and the pile length is 30m. The arch support is set on the abutment and shares the bearing platform for pile foundation with it, connecting the drill pouring pile foundation where D=1.2m and the pile length is 35m.

![Figure 3 Bridge Type Layout](image)

(a) Framing Elevation  (b) Cross-sectional Layout

Figure 3 Bridge Type Layout

As a landscape bridge of Double Happiness Island, this bridge has its own unique mechanic characteristics:

First of all, Double Happiness Island is an artificial land area and the bridge is a half-through arch structure in which the arch foot is pushing on the foundation. Since the artificial land has a limited capacity to bear horizontal thrust, the bridge should put the stress mainly on beams whose role needs to be given full play, and the arch ring assists in sharing some of the stress.

Secondly, since the arch axis is not a reasonable axis of arch, the ape of arch is the parabola, and the arch foot tends to be straight, the cable arrangement will be concentrated near the ape of arch.

Finally, the arch ring extends from the center line of the bridge to the anchor outside the bridge deck. The inhaul cables are arranged diagonally in space. The height of the arch ring should meet the requirements of clearance above bridge deck.

2. The Finite Element Model

The finite element analysis software MIDAS/Civil of the bridge major is used to establish a structure spacial model for the whole bridge, with the arch rib and the main girder simulated by the three-dimensional beam element, the hanger rod simulated by the truss element, the beam end simulated by the bearing of beams with simply supported ends, and the bottom of the arch rib consolidated and constrained with the central pier. For the safety consideration of foundation rigid constraints, six degrees of freedom of the arch foot and the central pile are totally consolidated.

The arch rib, the hanger rod and the main girder are positioned according to the real spatial location. The dispersion of main steel girders follows the stress model of grid beams consisting of I-shaped main girders and longitudinal secondary beams. The longitudinal beams are connected through real transverse diaphragms and cross beams.

![Figure 4 Sketch Map of the Spacial Model](image)
3. Calculation Results

3.1. Stress of the arch rib

(a) Stress on the upper edge of the arch rib in the main force combination
(b) Stress on the lower edge of the arch rib in the main force combination

(c) Stress on the upper edge of the arch rib in the main force + additional force combination
(d) Stress on the lower edge of the arch rib in the main force + additional force combination

Figure 5 Stress Diagram of the Arch Rib (Unit: MPa)

Table 1 Stress Sheet of the Arch Rib (Unit: MPa)

| Combination                              | Stress on the upper edge of the arch rib | Stress on the lower edge of the arch rib | Allowable stress |
|-----------------------------------------|------------------------------------------|------------------------------------------|-----------------|
| the main force combination              | 138.7                                    | 78.5                                     | 210             |
|                                          | -105.6                                   | -167.1                                   |                 |
| the main force + additional force combination | 164.4                                   | 151.6                                    | 252             |
|                                          | -188.2                                   | -189.8                                   |                 |

Note: In the table of this article, tension stress is positive and the compression stress is negative.

In the main force combination, the steel arch rib has the maximum compression stress of 167.1MPa and the maximum tension stress of 138.7MPa, all less than the stress allowed for the material $[\sigma] = 210$MPa. In the main force + additional force combination, the steel arch rib has the maximum compression stress of 189.8MPa and the maximum tension stress of 164.4MPa, all less than the stress allowed for the material $[\sigma] = 210 \times 1.2 = 252$MPa and 20%~25% more than needed. Therefore, the size of the arch rib needs no optimization design.

3.2. Stress of the longitudinal beam

In the main force combination, the longitudinal beam has the maximum compression stress of 148.9MPa and the maximum tension stress of 134.2MPa, all less than the stress allowed for the material $[\sigma] = 210$MPa. In the main force + additional force combination, the longitudinal beam has the maximum compression stress of 184.9MPa and the maximum tension stress of 164.5MPa, all less than the stress allowed for the material $[\sigma] = 210 \times 1.2 = 252$MPa and 25%~30% more than needed. Therefore, the longitudinal beam may need the optimization design.
Table 2 Stress Sheet of the Longitudinal Beam (Unit: MPa)

| Combination                      | Stress on the upper edge of the longitudinal beam | Stress on the lower edge of the longitudinal beam | Allowable stress |
|----------------------------------|--------------------------------------------------|-------------------------------------------------|------------------|
| the main force combination       | 134.7                                            | 95.7                                            | 210              |
| the main force + additional force combination | -92.3                                            | -148.9                                          | 252              |
|                                  | 167.5                                            | 119                                             |                  |
|                                  | -109.2                                           | -184.9                                          |                  |

3.3. Stress of the cross beam

Table 3 Stress Sheet of the Mid-support Cross Beam (Unit: MPa)

| Combination                      | Stress on the upper edge of the mid-support cross beam | Stress on the lower edge of the mid-support cross beam | Allowable stress |
|----------------------------------|--------------------------------------------------|-------------------------------------------------|------------------|
| the main force combination       | 79.8                                             | 1.2                                            | 210              |
| the main force + additional force combination | -1.7                                              | -82.2                                          | 252              |
|                                  | 95.2                                             | 3.2                                            |                  |
|                                  | -4.7                                             | -98.4                                          |                  |

In the main force combination, the mid-support cross beam has the maximum compression stress of 82.2MPa and the maximum tension stress of 79.8MPa, all less than the stress allowed for the material $[\sigma] = 210$MPa. In the main force + additional force combination, the mid-support cross beam has the maximum compression stress of 98.4MPa and the maximum tension stress of 95.2MPa, all less than the stress allowed for the material $[\sigma] = 210 \times 1.2 = 252$MPa and around 60% more than needed. Therefore, the mid-support cross beam may need the optimization design.

Table 4 Stress Sheet of the End Cross Beam (Unit: MPa)

| Combination                      | Stress on the upper edge of the end cross beam | Stress on the lower edge of the end cross beam | Allowable stress |
|----------------------------------|------------------------------------------------|------------------------------------------------|------------------|
| the main force combination       | 40                                             | 24.1                                           | 210              |
| the main force + additional force combination | -28.1                                            | -41.5                                          | 252              |
|                                  | 71.1                                            | 39                                             |                  |
|                                  | -41.3                                           | -76.2                                          |                  |

In the main force combination, the end cross beam has the maximum compression stress of 41.5MPa and the maximum tension stress of 40.0MPa, all less than the stress allowed for the material $[\sigma] = 210$MPa. In the main force + additional force combination, the end cross beam has the maximum compression stress of 76.2MPa and the maximum tension stress of 71.1MPa, all less than the stress allowed for the material $[\sigma] = 210 \times 1.2 = 252$MPa and 70~80% more than needed. Therefore, the end cross beam may need the optimization design.

Table 5 Stress Sheet of the Transverse Diaphragm (Unit: MPa)

| Combination                      | Stress on the upper edge of the transverse diaphragm | Stress on the lower edge of the transverse diaphragm | Allowable stress |
|----------------------------------|--------------------------------------------------|-------------------------------------------------|------------------|
| the main force combination       | 43                                              | 52.9                                           | 210              |
| the main force + additional force combination | -55.9                                           | -43.3                                          | 252              |
|                                  | 59                                              | 63.4                                           |                  |
|                                  | -66.1                                           | -56.2                                          |                  |

In the main force combination, the typical transverse diaphragm has the maximum compression stress of 55.9MPa and the maximum tension stress of 52.9MPa, all less than the stress allowed for the material $[\sigma] = 210$MPa. In the main force + additional force combination, the typical transverse diaphragm has the maximum compression stress of 66.1MPa and the maximum tension stress of 63.4MPa, all less than the stress allowed for the material $[\sigma] = 210 \times 1.2 = 252$MPa and around 73% more than needed. Therefore, the typical transverse diaphragm may need the optimization design.
3.4. Stiffness
Under lane loads, the main steel girder has the maximum deformation of 2.0mm upward, the
maximum deformation of 12.8mm downward and the total deformation of 14.8mm, which is less than
L/600=95mm. Therefore, the structural deformation meets the requirements.

The steel arch rib has the minimum camber of 6.0mm, the arch rib has the maximum camber of
6.0mm and the arch rib has the maximum lateral deformation of 12.0<26000/300=86.7mm. Therefore,
the structural deformation meets the requirements.

| Table 6 Displacement Gauge Under Lane Loads (Unit: mm) |
|-------------------------------------------------------|
| Location | Positive Displacement | Negative Displacement | Allowable Displacement |
|----------|----------------------|----------------------|------------------------|
| the longitudinal beam | Max | 2 | 12.8 | L/600=95 |
| min | 0.7 | 0.1 |  |
| the arch rib | Max | 6 | 0 | |
| min | 0 | -6 | 26000/300=86.7 |

3.5. The inhaul cable
Under various load combinations, the maximum tension of the inhaul cable is shown in Table 7, in
which the suspension cable adopts the 15-19 type cable body, the nominal cross sectional area is
26.6cm² and the breaking force is 4948KN. According to the calculation, the inhaul cable's coefficient
of safety is greater than 3.0, which meets the requirement.

| Table 7 The Cable's Tension Checking Table |
|-------------------------------------------|

| No. | maximum cable force (KN) | breaking force (KN) | safety factor |
|-----|--------------------------|--------------------|--------------|
| R-Y1 | 1260.1 | 4948 | 3.93 |
| R-Y2 | 1317 | 4948 | 3.76 |
| R-Y3 | 1261.2 | 4948 | 3.92 |
| R-Y4 | 1199.5 | 4948 | 4.13 |
| R-Y5 | 1069.4 | 4948 | 4.63 |
| R-Y6 | 1194 | 4948 | 4.14 |
| R-Y7 | 1300.6 | 4948 | 3.8 |
| R-Y8 | 1431.5 | 4948 | 3.46 |
| R-Y9 | 1592.5 | 4948 | 3.11 |
| R-Y10 | 1587.7 | 4948 | 3.12 |

| Table 8 The Cable's Tension Range Checking Table |
|-----------------------------------------------|

| No. | Maximum stress (Mpa) | Minimum stress (Mpa) | Stress difference (Mpa) |
|-----|----------------------|----------------------|------------------------|
| R-Y1 | 90.3 | -6.4 | 96.7 |
| R-Y2 | 98.9 | -7 | 105.9 |
| R-Y3 | 99.4 | -6.6 | 106.0 |
| R-Y4 | 82 | -11.1 | 93.1 |
| R-Y5 | 102.2 | -12.2 | 74.2 |
| R-Y6 | 116 | -11 | 77.6 |
| R-Y7 | 83.8 | -9.3 | 93.1 |
| R-Y8 | 99 | -7.2 | 106.2 |
| R-Y9 | 102.4 | -5.2 | 107.6 |
| R-Y10 | 95.2 | -4.1 | 99.3 |

Under various load combinations, the inhaul cable's tension range is shown in Table 8 with the
maximum tension range of 107.6Mpa and all less than the tension range allowed for the cable 200
MPa, which meets the requirement.

Since the inhaul cable's tension has a small amount more than needed, it needs no optimization
design.

3.6. Structural stability of the host bridge
The first-order buckling stability coefficient of safety of the bridge is 26.0, which is greater than 4 and
thus meets the requirement.

| Table 9 Structural Modal Table |
|--------------------------------|

| Modal No. | Critical load factor | Modal description |
|-----------|---------------------|-------------------|
| 1 | 26 | Out of plane buckling of arch rib chord |
| 2 | 27 | Out of plane buckling of arch rib chord |
| 3 | 28.3 | Overall out of plane buckling of arch rib |

4. The Optimization Scheme
In the original design, the main girder is a steel box girder with the girder height of 2.0m, the top plate
thickness of 16mm, the bottom plate thickness of 16mm, and the side web plate of 16mm. When the
distance from the middle supporting point to the left and right side is both 4.5m, the thickness of the top and bottom plate is adjusted to 25mm. When the distance from the middle supporting point to the left and right side ranges from 4.5m to 15.0m, the thickness of the top and bottom plate is adjusted to 20mm. Four longitudinal web plates are set up in the steel box girder, with its distance from the central line of the steel box girder being 1.5m and 6.1m. The typical distance between transverse diaphragms of the steel box girder is 3m, the diaphragm beams are filled with concrete at the end supporting points and the middle supporting points.

Through the finite element calculation, the arch rib and the inhaul cable need no optimization, and the longitudinal beam, the middle cross beam, the end cross beam and the transverse diaphragm may all need optimization. The specific optimization scheme is as follows:

1) The longitudinal beam: the longitudinal beam has 25% and 30% more than needed, so it has limited room for optimization. The height of the main girder is lowered from 2.0m to 1.9m, and the thickness is reduced by 0.1m as a whole.

2) The mid-support cross beam: the mid-support cross beam has around 60% more than needed. At present, filled with concrete, it has a width of 1.5m, which can be adjusted to 2.5m or even 2.0m.

3) The end cross beam: the end cross beam has around 70~80% more than needed. At present, filled with concrete, it has a width of 1.5m, which can be adjusted to 1.0~1.2m and meanwhile meets the width requirement of placing the support.

4) The typical diaphragm beam: the typical diaphragm has around 73% more than needed. At present, with a diaphragm not stiffened in between, it has the spacing of 3.0m. Its width can be adjusted to 4.0m, with the diaphragm not stiffened kept in between.

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