Study on Detail Constructions and Shear Lag Effect of a New Type Space-combined Tied Arch Bridge*

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Abstract: The First Zhongshan Bridge is a new type space—combined tied arch bridge composed of one middle arch rib, two side arch ribs and two seat arch ribs. The structure of the bridge is innovative and special, and almost no similar design can be found at present. Considering the detail constructions of the bridge play an important role in the load transferring, and the longitudinal girders of the bridge are in a form of box shape with a wide upper flange, based on a 1/10—scale model test a significant study on middle arch→seat arch→side arch cross beam joints, side arch→side arch cross beam joints and the shear lag effect of the longitudinal box girders were carried out. A 3D shell finite element model of the model bridge was developed and finite element analysis was performed to obtain the theoretic results, then to predict the structural behavior and guide the test loading. By comparison of the test results with the theoretical ones, the values were in good agreement, and the maximum stress under the extreme load were all far below the allowable values, thus the detail constructions of the bridge were proved reasonable and safe. Further study indicated that cross beams and axial forces have great influence to the shear lag effect of longitudinal box girders under full dead load.

Key words: space-combined tied arch bridge; steel bridge; model experiment; detail constructions; shear lag effect; FEA
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The First Zhongshan Bridge, which crosses the Qijiang River, is located at the downtown of Zhongshan City, Guangdong Province. The bridge is a new type spaced—combined tied arch bridge composed of one middle arch rib, two side arch ribs and two seat arch ribs. Design of the bridge is innovative and special, and almost no real cases of the similar design can be found at present. It is also the first time for the space—combined steel arch bridge design to be applied in China. The overall span of the bridge is 30 m + 100 m + 30 m with bridge width 36.8 m. The span of the middle arch rib is 120 m, rise span ration of which is 1/6; The span of side arch rib is 100.0 m, which is inclined at 11.40 from the vertical direction and it's rise span ration is 1/3.769; The span of seat arch rib is 32.968 m, which is inclined at 42.630 from the vertical direction, and it's rise span ration is 1/2.997. Longitudinal box girders of the bridge use two separated single—box double—rooms flat—box orthotropic steel girders with a height of 1.3 m and a length of 160m. The width of top flange of a single longitudinal box girder is 12.5 m, and the bottom flange width is 5.48 m, so the ratio of span to width is 8. At the interior span, one suspender cross beam is set at a distance of 5 meters which connects the two longitudinal box girders, whereas at the side span, there is no any cross beam set except for the end cross beams and side arch cross beams. The bridge was open to traffic at the end of 2005, and now it is one of the symbolic constructions of Zhongshan City.

Considering the complexity of loading condition and loading transfer characteristics of the detail constructions of the bridge such as middle arch→seat arch→side arch cross beam joints and side arch→side arch cross beam joints, for evaluating the capability of the safety reserve of detail constructions of the bridge, validating the rationality of design theory, and optimizing the design parameters, and discovering and compensating for the uncertain and weak parts of both joints, 1/10—scale model test was performed. Fig.1 shows the picture of the model bridge of First Zhongshan Bridge. Since the longitudinal box girders of the bridge have a wide flange which may result in significant shear lag effect, the model test provided a good opportunity to study the shear lag effect to ensure safety[1-2]. Shear lag effects have been studied for many

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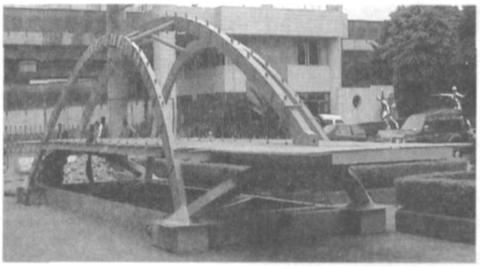

Fig. 1　Model bridge of the Zhongshan First Bridge

decades, however investigators mostly only paid attention to simply supported beams or continuous beams under concentrated and uniform load[3-4]. Few focuses on the study on shear lag effect of longitudinal box girder of space-combined arch bridge, which subjected to combined bending and axial loads.

1　Model design principle

For the model bridge, design principle of stress similarity and stiffness similarity are adopted, if there is a conflict, stress similarity has the priority. The ratio of geometry is: 1/10; stress: 1/1; mass: 1/1000; moment of inertia: 1/10000; elastic modulus: 1/1; displacement: 1/10. There are eight points supports in vertical direction, and four points constraints in horizontal direction.

As for the actual bridge, the length, width and height is 163 m, 39.4 m and 29.9 m, respectively. According to the similitude theory, for the model bridge, the length, width and height is 16.3 m, 3.94 m and 2.99 m, respectively, and the thickness of steel arch ribs is 1.8 mm. Because the model are mainly static and no impact and fatigue test are involved, the thickness of the arch ribs and longitudinal girders and cross beams of the model actually is 2.0 mm in thickness instead of 1.8 mm. The identity of vertical bending stiffness and the stresses between the model and the actual bridge are ensured by reducing the cross-section width. In order to ensure the stiffness matching of the bridge deck, similarity theory is utilized to simplify the structure, which means adjusting the bridge width while keeping its height. For facilitating the welding process and ensuring the in-plane bending stiffness and stresses identify to the real structure, the cross-section geometry is changed to ‘I’ geometry[5]. Model joints of middle arch→ seat arch→ seat arch cross beam and side arch→ side arch cross beam are critical parts of the structure. In order to facilitate the welding process for the model fabrication, the design of the joints were slightly different from the real structure. This adjustment was based on the 3-D calculation results, and stress condition of the model is almost identical to the real structure[6-7].

2　Finite element model

For guiding the model test and predicting the structure behavior, a 3-D shell element model was established with FEM program ANSYS to perform the finite element analysis. The top plates, bottom plates, webs, diaphragms of box longitudinal girders, suspender cross beams, side arch cross beams, middle arch cross beams, end cross beams, cantilever cross beams, middle arch rib, side arch ribs, seat arch ribs, transverse braces, cap piles were divided into 4-node shell elements. Link element was employed to model the members such as the suspenders, tie of middle arch rib. 4-node solid element was used to model the concrete parts of side arch ribs and seat arch ribs. One vertical point constraint was set under each cap pile, meanwhile one horizontal point constraint was set on side of each cap pile in transverse and longitudinal direction respectively.

3　Test program

For evaluating the critical stresses of the joints of middle arch→ seat arch→ middle arch cross beam, joints of side arch→ side arch cross beam, and shear lag effect of longitudinal box girders, test loads were simulated by applying cast iron weight or iron bar, and weight could be loaded by two modes, i. e. heap load on deck or hang gasket. The following loading programs were carried out in laboratory environment. In order to make sure that the loading and unloading process are simultaneous, symmetrical and uniform, the position of the loading and the whole process was precisely calculated for each loading program.

3.1　Middle arch→ seat arch→ side arch cross beam joints loading program

Based on the results calculated under combination of dead load and worst live load of actual bridge, the maximum axial force of middle arch springing is 7 640 kN[8-9]. To check the safety and rationality of the joints of middle arch→ seat arch→ middle arch cross beam, according to theory of similarity, only the middle arch springing will reach 70～80 kN axial force by middle arch→ seat arch→ middle arch cross beam joints loading, the reaction of the model bridge can be similar to the actual bridge. Through calculating trail and error, three loading modes including bridge deck heap loading, middle arch rib hang loading, and middle of suspender cross beam hang loading have been applied. By use of 320 kN weight, 72 kN axial force was produced at middle arch spring, then basically it was similar to the actual bridge At the same time the stress of other members have been checked and all below allowable stress In the whole loading process loads were divided into 5 levels which increased gradually to ensure that the loading mode was safety and effective

3.2 Side arch－side arch cross beam joints loading program

According to the results calculated of actual bridge it shows that the stress state of side arch cross beams is complicated axial force biaxial shear force torsion biaxial bending all exist at the same time[8-9]. The main factors are vertical bending and transverse bending the bending stress at the joints between side arch and side arch cross beam has reached 66.5 MPa under the combination of dead load and worst live load To check the structure's safety and rationality of side arch→ side arch cross beam joints according to theory of similarity the bending stress at the joints between side arch and side arch cross beam should reaches 66.5 MPa[8-9]. Through calculating trail and error the bending stress at the joints reached 67.5 MPa with 160 kN weight by deck heap load then on the whole the reaction of the model bridge was similar to the actual bridge The stresses in the other members were all under the allowable stress by check The total loads were divided into 5 levels

4 Test and analysis

4.1 Detail constructions

In order to obtain the stress distribution pattern strain measure points and were set on the key parts of the bridge

This paper only addresses representative values from the experimental results Detailed experimental results can be found elsewhere[8]. A summary of the experimental results are provided and compared with calculated ones Strain values of key members under middle arch→ seat arch→ side arch cross beam joints loading case and side arch→ side arch cross beam joints loading case are tabulated in Table 1 and Table 2, respectively

Table 1 shows that the maximum experimental strain of main members of the bridge produced by middle arch→ seat arch→ side arch cross beam joints loading is －272.7 με, correspondingly the stress is about －55 MPa which is at the position of upper flange of cross section at quarter middle arch As seen from Table 2, the maximum experimental strain of main members of the bridge produced by side arch→ side arch cross beam joints loading is －444.3 με, correspondingly the stress approximates －90 MPa which occurs at the lower flange of cross section at quarter span of interior longitudinal girder All the experimental stress results are below 100 MPa which are far below the allowable stress of Q345 steel consequently it is found that all local stresses not only satisfy the requirement of "Design Specification for Steel Structure and Wood Structure of Highway Bridge and Culvert", but also have good safety margin[10].

All the results from test and theoretical calculations indicate that the actual bridge has enough strength storage therefore design of the member sections middle arch→ seat arch→ seat arch cross beam joints and side arch→ side arch cross beam joints are reasonable and safe

Tab.1 Strain of cross sections of key members under middle arch→ seat arch→ side arch cross beam joints loading case (με)

Side face of cross section at middle arch springing		Upper flange of cross section at middle arch springing		Upper flange of cross section at quarter middle arch		Lower flange of cross section at side arch springing	
Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
－99.3	－97.0	－101.3	－81.6	－272.7	－283.0	－229.3	－280.0

Note: "－" indicates that the stresses are compressive

Tab.2 Strain of cross sections of key members under side arch→ side arch cross beam joints loading case (με)

Lower flange of cross section at middle arch springing		Lower flange of cross section at quarter span of longitudinal girder		Upper flange of cross section at side arch springing		Lower flange of cross section at side arch springing	
Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
－194.0	－155.0	444.3	476.7	79.8	89.9	－239.2	－217.0

Note: －" indicates that the stresses are compressive

From Table 1－2, although comparisons between experimental data and results obtained from finite element analyses show good predictions of the structural behavior some measured values are still different from calculated results to some extent Discrepancies aroused mainly attributed to some factors i e horizontal constraints of model bridge were elastic supports however the theoretical calculation did not consider the elastic deformation of horizontal constraints Furthermore because the bridge is a high order statically indeterminate structure the temperature especially the change of the environment temperature has a large influence to the reaction besides the precision of strain gauge under small loading the fabrication error of the testing model will all lead to some difference between experiments values and theoretical ones

4.2 Shear lag effect

To study the shear lag effect of the longitudinal box girders the cross sections at center position quarter position and eighth position of longitudinal box girders between both side arch cross beams side arch cross beams and seat arch cross beams and end cross beams and seat arch cross beams were chosen. There were 14 sections for the measurement of stress of shear lag effect as depicted in Fig. 2. At each section a total of 18 gages are placed at the upper and lower flanges of the single box girder

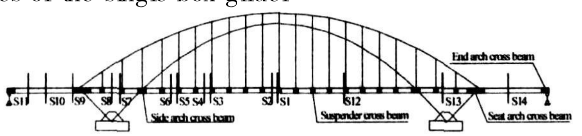

Fig. 2　Sections measured along the longitudinal box-beams

Fig. 3—6 illustrate that under full dead load the stress distribution patterns of upper and lower flanges of longitudinal girder are non—uniform due to shear lag effect of box longitudinal girders and the shear lag effects vary in different locations along the longitudinal box girders Generally the shear lag effects are larger on the upper flanges and smaller on the lower flanges

As observed from Fig. 4—6, section s1, s3, s5 and s7 are all close to suspender cross beams and shear lag effects of section s1, s3, s5 and s7 are less apparent than those of section s2, s4, s6 and s8, so it can be concluded that the suspender cross beams can restrain the shear lag effects of longitudinal box girders effectively

Shear lag effects of longitudinal box girders between seat arch cross beams and side arch cross beams are most predominant whereas those of longitudinal girders between end cross beam and seat cross beam are less obvious which maybe due to the influence of axial forces or support conditions According to the calculation values of the actual bridge under the full dead load (combination of first stage dead load and second stage dead load), the longitudinal girders between both seat arch cross beams are subjected to combination of bending moment and axial force while the longitudinal girders between end cross beams and seat arch cross beams are only subjected to bending moment[6]. Axial force produced by full dead load of longitudinal box girders between two side cross beams is 2.56×10^{7} N, between side arch cross beams and seat arch cross beams is 3.64×10^{7} N, and there is no axial force between end cross beams and seat arch cross beams As regard the relationship of axial forces and shear lag effect of box girders it can be found that the larger the axial force the more shear lag effects appear

The First Zhongshan Bridge can be regarded as not only a beam—arch multipoint consolidation combined system but also a suspended elastic support system. Considering the limit of paper size and complicity of support system, this paper didn't take into account influence of support conditions such as seat arch or suspender to shear lag effects of longitudinal box girders

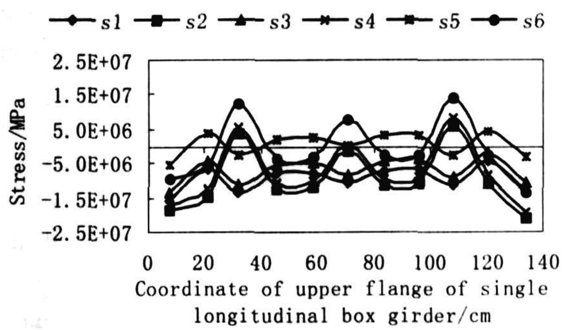

Fig. 3　Shear lag effects of upper flange of section s1～6

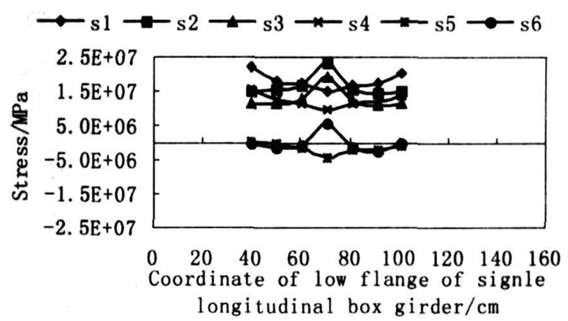

Fig. 4　Shear lag effects of lower flange of section s1～6

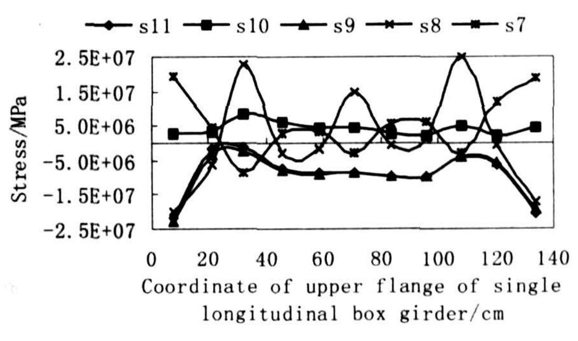

Fig. 5　Shear lag effects of upper flange of section s7～11

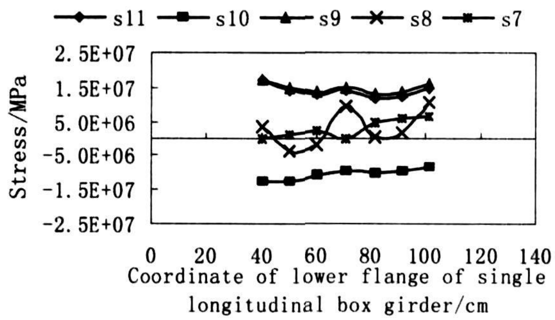

Fig. 6 Shear lag effects of lower flange of section s7 ～s11

5 Conclusions

Based on the preceding model test and calculated results conclusions and suggestions are summarized as follows:

(1) The strength and stiffness of middle arch→seat arch→ middle arch cross beam joints and side arch→ side arch cross beam joints have good safety margins thus the detail constructions of First Zhongshan Bridge are verified safe and reasonable

(2) The shear lag effect of the box longitudinal girders are obvious therefore it can not be neglected in the design of similar cases especially the shear lag effects of upper flanges are larger than those of lower flange

(3) Cross beams and axial force of longitudinal box girders have great influence to the shear lag effects of box girders furthermore study indict that the cross beams can restrain the shear lag effectively

(4) The bridge is a high order statically indeterminate structure the temperature especially the change of the environment temperature has a large influence to the reaction so it is necessary to pay more attention to the construction fold temperature paint spreading and control these factors in construction process

(5) Comparisons between available experimental results and results obtained from finite element analyses show good predictions of the structural behavior so it is considered that FEA is an effective method for the understanding of the behavior of bridge structure

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新型空间组合拱桥细部构造和剪力滞效应的研究

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摘 要： 中山一桥是由一片中拱肋，两片边拱肋以及两片座拱肋组成的一种新型空间组合钢拱桥，该桥造型新颖独特，在国内外应用尚属首次。考虑到该桥细部构造在力的传递方面起关键作用，并且纵梁梁截面形式为挑臂较大的单箱双室箱形结构，所以基于 1∶10全桥试验模型，对中拱→座拱→边拱横梁结点、边拱和边拱横梁结点的细部构造以及纵向箱梁的剪力滞效应进行了试验研究，同时建立了空间三维全桥板壳模型用来校核试验结果、指导模型试验加载。通过试验结果与理论结果的比较可以看出二者基本吻合，试验和理论结果均表明在最不利荷载作用下该桥最大应力远小于设计容许值由此证明该桥细部构造设计是合理安全的。进一步的研究表明，在恒载作用下该桥纵梁的剪力滞效应受横梁、轴力的影响很大。

关键词： 拱桥；钢桥；空间组合拱桥；模型试验；细部构造；剪力滞效应； FEA

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