Experimental and Numerical Study on Compressive Behaviour of Convex Steel Box Section for Arch Rib

Nagasaki University Member Shozo Nakamura
Nagasaki University Student Member ○KangMing Chen
Nagasaki University Member Takafumi Nishikawa

1．Introduction

Yongjing Bridge is located at the east outer-ring of Ningbo City, China (see Fig. 1). The each rib of the bridge has both upper and lower limbs, and sections of the middle half of the arch ribs have the convex shapes due to the joint of the upper and lower boxes (see Fig. 2). Since this convex section has been rarely employed in existing bridges in the world, there is no established engineering experience and provisions for reference. This Bridge was designed according to the *specifications for highway bridges* published by Japan Road Association. The design method for compressive strength of normal steel box was employed to design the convex sections to guarantee the local stability.

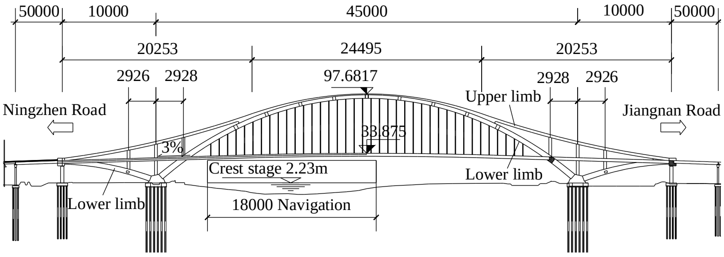

Fig. 1 General view of Yongjiang bridge (Unit: mm)

To reveal the actual bearing capacity and local instability mechanism of a convex steel section for arch rib considering the initial imperfections and local buckling, a loading test using 1/4 scale-model and nonlinear FE analysis were conducted.

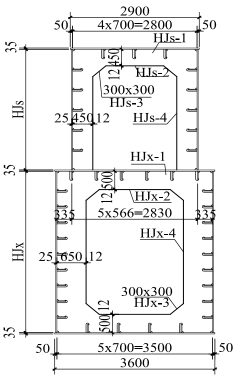

Fig. 2 Cross-section of the arch rib (Unit: mm)

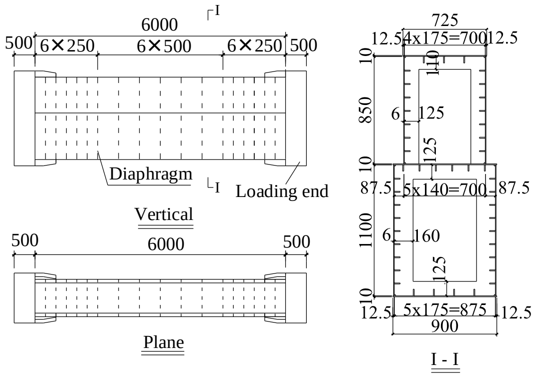

Fig. 3 General layout of reduced scale model (Unit: mm)

2．Outline of Reduced Scale Model Test

A 1/4 scale model of the section at L/4 point was used for the test. The general layout and completed model is illustrated in Figs. 3 and 4, respectively. The completed reduced scale model was placed on two foundations with rollers, and the interfaces between model and roller were painted with machine oil. The both ends of the model were strengthened by the steel-concrete composite structures for easy and uniform loading, which were integrated with the main part of the model by some stiffeners. In order to avoid local buckling in the section close to both ends due to stress concentration during loading, the intervals of diaphragms within 1.5m from either end were shorten to the half of that in the middle portion, as shown in Fig.3.

Fig. 4 Completed reduced scale model

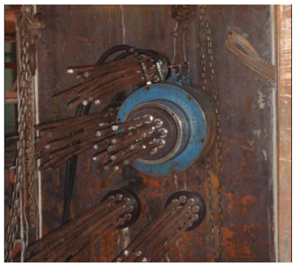

Fig. 5 Loading by prestress wires

The prestress wires were adopted to apply the load, as shown in Fig. 5. There were 9 holes along the axial direction for the prestress wires to pass through, and the centroid of holes coincided with that of the cross section. The prestress wires were anchored at one side, and stretched at the other side hole by hole to apply the axial compressive load.

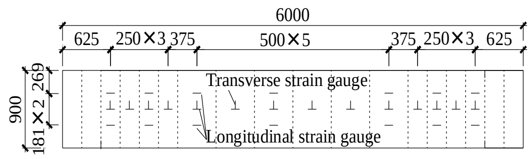

Fig. 6 Distribution of strain gauge in middle plate

Fig. 7 Displacement meter

The in-plane strains and out-of-plane deflections were mainly measured during the loading process. For monitoring the location of local buckling, the strain gauges were placed in lines and along the longitudinal direction of the plates. The position of strain gauges on middle plate is shown in Fig. 6. Those on top, bottom and web plates are similar to middle plate. For monitoring the local deformation and integral slippage, 3 vertical and 1 longitudinal displacement meters were placed at the top plate, bottom plate and the two web plates, respectively, as shown in Fig.7.

3．Outline of FE analysis

The FE model for reduced scale model were developed and analyzed by using MSC.MARC, as shown in Fig.8. The element No.75 (shell element) was used for the whole model except the both loading ends of reduced scale model where they were modeled by element No.7 (solid element). The size of each element was approximately 12.5cm. The

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Corresponding Address: Department of Civil Engineering, Nagasaki University, 1-14, Bunkyo-machi, Nagasaki City, 852-8521. Tel.: 095-819-2613, Fax: 095-819-2627.

vertical and lateral translations of the FE model were fixed at the bottom of both loading ends. In addition, the axial loads were applied to the center of the holes. The initial stress and geometric deflection were considered. The constitutive relationships of stiffened plates and stiffeners were inputted according to material test. The yield stresses of which are σ_p=359.7MPa and σ_s=371.5MPa, respectively. Large deformation effects were considered by the updated Lagrangian formulation. The nonlinear equilibrium equation was solved by the arc-length method.

4. Results and Discussions

4.1 Validity of Loading Test and FE Analysis

The section average stress can be obtained by dividing the axial compressive load by section area, and the measured stress is calculated from the measured strain. Taking middle plate as an example, the distribution of measured and FE analysis stress in lengthwise direction is illustrated in Fig. 9 with corresponding section average stresses. It is shown that the measured stresses are close to section average stresses except some points adjacent to loading ends. It indicates that the loads are applied along the centroid of convex section, and both loading ends could transmit the loads effectively. The measured and FE analysis stresses show fairly good agreement. It can be thought that the FE model is appropriate, and could simulate the behavior of the specimen.

4.2 Strength Reduction Coefficient

According to FE analysis, the relationship between section average stress and equivalent strain △/L are compared with that of loading test in Fig. 10. It shows that the ultimate section average stress is 355.7 MPa. According to the *specifications for highway bridges*, the ultimate axial compressive stress of the convex section equal to yield stress. Which is $\sigma=(\sigma_p\times A_p+\sigma_s\times A_s)/(A_p+A_s)$=365.2MPa. A_p and A_s are the total section area of stiffened plates and stiffeners, respectively. Providing the strength reduction coefficient considering local buckling is $\beta=\sigma_{cal}/\sigma$, therefore, the strength reduction coefficient by FE analysis was β=355.7/365.2=0.97.

4.3 Buckling Deformation and Integral Buckling Mode

After loading test, no local buckling and obvious deformation were observed in the reduced scale model, except a few longitudinal stiffeners close to the middle plates, as illustrated in Fig. 11. The deformation of convex section in FE model under the ultimate load can be seen in Fig. 12. It is shown that deformations of the stiffeners near the corner were larger than those of the others, and the deformation of the stiffeners near the middle plate had the maximum value. It was similar to the experimental results. It indicates that the local buckling of stiffened plates could be prevented effectively by stiffeners and diaphragms, but attentions should be paid to the design of longitudinal stiffeners near by the location of two primary plates connected, especially the longitudinal stiffeners close to the middle plate.

Since obvious buckling deformation didn't take place under the load applied by limited prestress wires, the integral deformation form of the reduced scale model under the ultimate load was obtained by FE analysis, as illustrated in Fig. 13. Under the ultimate load, the stresses of stiffened plates were slightly larger than yield limit, and ripples appeared in the middle portion of model. It indicates that the reduced scale model fails to resist larger applied load due to the extensive out-of-plate deformation of stiffened plates.

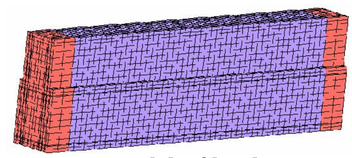

Fig. 8 FE model of loading test

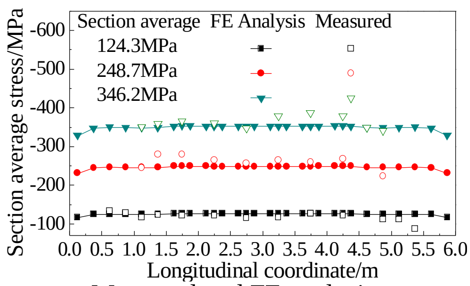

Fig. 9 Measured and FE analysis stress

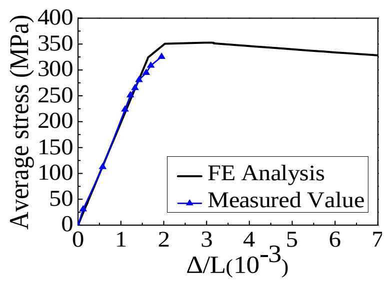

Fig. 10 Relationship between stress and △/L

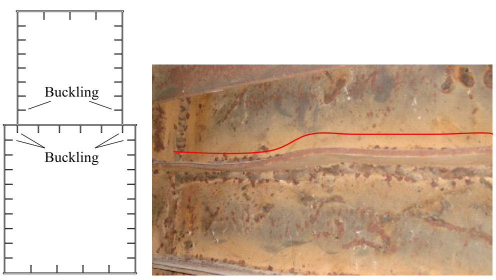

Fig. 11 Buckling location and shape

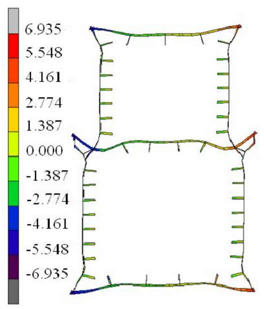

Fig. 12 Deformation of convex section

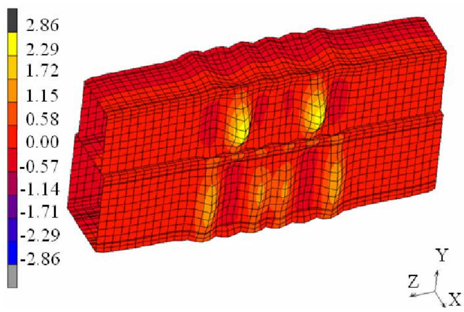

Fig. 13 Integral deformation form

5. Conclusion

The bearing capacity and local instability mechanism of convex steel section for arch ribs of Yongjiang Bridge were studied considering the initial imperfections and local buckling by axial compressive loading experiment on a 1/4 scale model and FE analysis. It was found that the strength reduction coefficient of convex steel section is 097 by FE analysis. Although the local buckling of stiffened plates can be prevented effectively by stiffeners and diaphragms, attention should be paid to the design of stiffeners near the location of two stiffened plates connected. The reduced scale model fails to resist larger applied load due to the extensive out-of-plane deformation. Going forward, the parameter analysis of convex section will be studied to reveal the reasonable design and applicability of specification for convex section.