Model Experiment of Construction Process of Long-Span Concrete Arch Bridge Rigid Skeleton

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Abstract. High-speed railway passenger dedicated line have high demands for track smoothness, beipanjiang bridge as shanghai-kunming high-speed railway control project, mainspan 445m, constructed by using rigid skeleton, C80 high-strength concrete filled steel tube structure for the first time used in railway bridge; rigid skeleton in the process of construction has the traits: long span, long construction period, multi-step, mechanical behavior was extremely complex. In this paper, the design principle and similarity relation of rigid skeleton model are introduced, simplified the model construction process, and the finite element simulation analysis model is established, compared with measured values, it is shown that model test can well simulate the long span rigid skeleton arch bridge stress state in the construction process; the original construction steps have more safety reserves than simplified; the indicators of model test are within the scope of design, the results can provide technical support for the bridge construction.

1. Introduction

The stiff skeleton method, also known as embedded arch method, was first proposed by Czech engineer Joseph Melan in 1898, which greatly improved the spanning capacity of reinforced concrete arch bridge. The traditional stiff skeleton is mostly steel structure, and while increasing the stability of the skeleton, the material was wasted and poor economic. In the 1990s, China began to apply the concrete-filled steel tubular structure to the arch bridge. The truss structure composed of upper and lower chord of the concrete-filled steel tube structure greatly improved the overall stability, stiffness and economy of the stiffened skeleton, and the concrete-filled steel tubular structure has the characteristics of high compressive strength and good ductility, so it’s a very competitive construction method for long-span reinforced concrete arch bridges. China has built many long-span concrete bridges with concrete-filled steel tubular stiff skeleton method, such as Wanxian Yangtze River Highway Bridge with main span of 420m, Guangxi Yongning Yongjiang Bridge with main span of 312m, Yungui high speed railway Nananjiang Bridge with main span of 416m and Hukun high speed railway Bridge with main span of 445m, Japan also built the Qingye Bridge with a main span of 180m, Usagawa Bridge with a main span of 204m and the Takamatsu Bridge with a main span of 260m. Scholars of china and abroad have explored the ultimate span of reinforced concrete arch bridges[1, 2], the breakthrough is mainly in construction, and the application of the stiff skeleton method has promoted the further development of the span of concrete arch bridges[3-10].
2. Engineering Background
The total length of Beipanjiang River Bridge is 721.2m, and the mainspan is 445m high-strength concrete arch bridge and the height is 100m, the span ratio is 1/4.45, an arching coefficient of 1.6, and a single box of three chambers, contour and variable. Wide box section, the arch ring height is 9m, the arch ring outer wrapped material is C60 concrete, the steel tube concrete is used for the skeleton method construction, the steel tube is filled with C80 high-strength concrete. the highest design speed is 250km/h, and the reserves speed is 350km/h. The general layout of the bridge span is shown in figure 1.

![Figure 1. Layout of Beipanjiang bridge.](image)

3. Design and Production of the Stiff Skeleton Model
3.1. Similarity principle and design of stiff skeleton model
In principle, the geometrical dimensions of the model should be strictly according to the similarity ratio of 1/7.5. The span of the model is 59.333m, the height is 13.413m, the arch axis coefficient is 1.6, and the diameter of the steel tube is 102mm. The schematic diagram of the stiff skeleton structure is shown in figure 2 and figure 3.

![Figure 2. Elevation of rigid skeleton model.](image)  
![Figure 3. Plan of rigid skeleton model.](image)

3.2. Model material and product
According to the model design principle and the purpose of the experimental research, the model is made of the same material as the actual structure, that is, $C_E=1.0$ and $C_μ=1.0$. In the process of model making, some model materials were properly adjusted due to factors such as material purchase, processing and on-site construction conditions. The comparison between the final stiff skeleton model and the main materials of the original bridge is shown in table 1.

| structural element                  | Skeleton model         | Prototype       |
|-------------------------------------|------------------------|-----------------|
| Rigid frame steel tube              | Q345B steel            | Q370qC steel    |
| Connection system Angle steel, joint plate, stiffening rib | Q235B steel           | Q345B steel     |
| Stube-filled concrete               | CGM Bridge special high Strength self - compacting mortar | C80 concrete    |
According to the geometric similarity scale, the inner diameter of the stiff skeleton steel tube is only 94mm, and the concrete strength in the original bridge tube is C80, the coarse aggregate particle size is 5mm~20mm, and the fluidity is bad, so fine stone concrete was selected, and good test results were obtained at the same time as the construction. In order to prevent the tube blocking phenomenon during the pouring process, by collecting data and comparison, we determined to use the high-strength self-compacting CGM mortar for bridge. Since CGM mortar does not contain coarse aggregate, the material test results are shown in table 2.

Table 2. CGM bridge dedicated high-strength self-compacting mortar material test results.

| Material     | Cube compressive strength /MPa | Elasticity modulus /MPa | Initial mobility /mm | 30mins Fluidity retention value /mm |
|--------------|--------------------------------|-------------------------|----------------------|-------------------------------------|
| CGM Mortar   | 43.6                           | 66.6                    | 3.52×10⁴             | 373                                 |

4. Model Measured Points Arrangement

The test during the construction of the model includes the strain test and displacement test. The stiff skeleton model has a total of seven strain test sections, which are the two sides of the arch, L/8, L/4, L/2, 3L/4 and 7L/8 section, strain test sections shown in figure 4.

The strain test layout of each section of steel tube is shown in figure 5. G1~G8 are steel tube strain measuring points, and each test section is arranged with 8 steel tube strain measuring points. The whole bridge has a total of 56 steel tube strain measuring points.

Figure 4. Layout of strain test section/mm.

Figure 5. Layout of Strain measuring points.

A total of 7 displacement test sections are arranged in the stiff skeleton model, which are L/8, L/4, 3L/8, L/2, 5L/8, 3L/4 and 7L/8, as shown in figure 6.

A displacement measuring point is arranged on each of the upper outer steel tube of each displacement measuring point section, the displacement test and the strain test are simultaneously performed, and the displacement measuring points of each test section arrangement as shown in figure 7.

Figure 6. Layout of displacement test section/mm.

Figure 7. Layout of displacement measuring points.
5. Establish Finite Element Model and the Analysis of Test Results

5.1. Modeling ideas and model building
Establish a finite element calculation model with MIDAS/Civil to analyze the construction stage. The core concrete is subjected to less compressive stress during the construction stage, and the tight force of the steel tube has not yet been exerted. Therefore, the interaction between the steel tube and the core concrete, geometric nonlinearity and the influence of material nonlinearity are not considered. The finite element model was shown as figure 8.

![Figure 8. Finite element model.](image)

5.2. Analysis of test results
The stiff skeleton model mainly controls the distribution of stress and displacement of the upper and lower string steel tubes under the main working condition as shown in figure 9-12. The changing curve of the main control sections steel tubes stress under various load conditions are shown in figure 9, 10. During the model test, the steel tube stress of the main control sections are in the 2# working condition to the 3# working condition increase is the largest, in which the stress of lower chord of the arch foot section and the cross-section of midspan increase 125.0 MPa, mainly because the concrete weight in the tube is loaded in the 3# working condition, and the applied load is large, but only the steel skeleton bear the load. In the process of web construction, in order to simplify the calculation, a one-time casting method is adopted, and the weight of the web is relatively large. Therefore, in the 15# working condition, the stress of the steel tube of the 2#–6# section increase greatly. Among them, the stress increase of the chord on the middle section is the largest, reaching 71.0 MPa, and the cross section of the arch foot section has formed a full section at this time, the concrete begins to be bear the load, and the stress increase of the steel tube is not so obviously.

The displacement changing curve of the main control sections under various load conditions are shown in figure 11, 12. The measured values of the 1/8 section is larger than the calculated values. In the 14th and 15th load cases, the measured values reached 1.5 times of the calculated values due to the second section of the full-section outer concrete is poured, the strength is not up to the design values, and the shrinkage and creep value of the early-age concrete is large, so that the measured value is significantly higher than the theoretical value, and the remaining sections are The measured values of the displacement agree well with the theoretical values, and the coincidence rate is about 90%.
6. Conclusions
Beipanjiang Bridge as the world's largest span high-speed railway stiff skeleton concrete arch bridge, the compression performance of high-strength CFST concrete structure can be fully exerted, and the structural stress and displacement changes are uniform and reasonable, which fully guarantees the safety and stability of the whole bridge construction.

The measured results and calculation results of the stiff skeleton model show that the main control sections have a large stress increase in the third load condition, and the stress increase of the chord and the mid-section of the arch section reaches 125.0MPa. and the 2#~6# sections steel tubes also appears large increase under the 15th load condition. The stress increase of the chord on the mid-section is 71.0MPa, In the construction process of the original bridge, it is necessary to pay attention to the stress changing of the steel tubes of the arch foot section and the mid-section to prevent the stress from exceeding the limit values and affect the structural safety.

During the construction of the model, due to the limitation of construction conditions, it is difficult to ensure the symmetric loading of the weights, so in the original bridge construction process should be ensure the symmetry of concrete pouring, to prevent excessive stress on the local steel tube, affect the stability of the full bridge structure.
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