Parametric Analysis and Research on Full-range Mechanical Behavior of Curved Twin-I Girder Composite Bridges

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Abstract. In order to further study the full-range mechanical behavior of the curved and small- and medium-span twin-I steel girder composite bridges, the combination of experimental verification and numerical analysis was used to study the stability safety at construction stage and ultimate strength at finished stage of the curved continuous composite beam of 35m standard span. Firstly, using the experimental data in the literature, the ABAQUS nonlinear numerical model was verified from the aspects of failure load and mid-span deflection. Secondly, the stability safety factor and the ultimate live load coefficient were used as indicators to compare and evaluate the mechanical performance of the full bridge structure with different spans and different curvature radius. The results show that the stability safety of three-span bridge improved obviously compared with the simply supported beam, but ultimate strength of bridges with different spans is similar at finished step. The stability safety and ultimate bearing capacity increased with the increase of the radius during the whole process. When the curvature radius is greater than 460m, the bearing capacity is significantly improved. According to the difference of live load coefficient of inner and outer curved girder, the design could be referred to different inner and outer girder height.

1. Introduction

I-girder steel concrete composite bridges is the most commonly used composite beam form for small and medium span bridges. The design and construction conditions are wide. At present, the development trend of composite bridge is the form of less main girder and simplified stiffener.

A great deal of research has been done on the mechanical properties and ultimate bearing capacity of single beam or box-section composite beam bridges. Shuyu Qi\textsuperscript{[1]} carried out a cantilever loading test on steel-concrete curved composite box girder, and studied the bending and torsion behavior of the structure. Xuefei Shi\textsuperscript{[2]} comprehensively considered the factors of bending stress, ultimate bearing capacity of the system, and analyzed the mechanical behavior of the twin-I girder composite bridges by finite element method. Huachen Liu\textsuperscript{[3]} studied the influence of cross-linking and main beam spacing on the overall torsional behavior of twin-I girder steel concrete composite bridges. Weiwei Lin\textsuperscript{[4]} studied the behavior of single beam form of curved I-beam composite bridges with different central angle under negative bending moment and torque at elastic and elastoplastic stage.

At present, the research on the I-girder steel-concrete composite bridge is mostly carried out in the aspects of bending, torsion, shearing resistance and working performance of the negative bending moment of the single-beam. For the double main girder or multi-main girder structure, the study of full-range mechanical behavior is not deep enough. Based on the shortcomings of the above research,
this paper studies the stability and safety performance of the construction stage and the ultimate bearing capacity of the finished stage of the 35m standard span curve twin-I beam in actual engineering. Perform parametric analysis to determine the reasonable number of spans and radius of curvature.

2. Engineering Situation

This paper relies on the engineering as a 35m standard span combined continuous beam bridge with a flat curve radius R=460m. The main beam adopts Q345qDNH double-I straight steel plate composite beam, the single-lane road plate width is 12.75m, the steel main beam standard spacing is 6.7m, and the main beam height is 1.8m. There are 4 small beams in the cross, and the longitudinal spacing is 7m. The bridge deck is made of C50 concrete and the longitudinal reinforcement grade is HRB400. The design parameters of the steel beam structure are shown in Table 1, and the cross-sectional view of the main beam is shown in Figure 1.

| Radius of curvature /m | Section's location | Steel beam size/mm |
|------------------------|--------------------|--------------------|
|                        | Girder height      | Web thickness      | Top flange plate | Bot flange plate |
|                        | 1800               | 20                 | 800 | 28 | 960 | 54 |
|                        | Intermediate support | 1800               | 28  | 800 | 48  | 960 | 60 |
|                        | Side support       | 1800               | 20  | 800 | 22  | 960 | 40 |

Figure 1. Dimensions of cross section of curved steel-concrete composite beams

3. Finite Element Model

3.1. Establishment of nonlinear analysis model

In this paper, the full-scale force analysis of the steel plate composite beam is carried out by using the Standard module in the large-scale finite element software ABAQUS. In the finite element model, a rigid block with large rigidity is used to simulate the support and the load pad to avoid stress concentration at the loading position on the block and the steel beam [5]. The literature [6] indicated that the CDP model can accurately simulate the mechanical response of concrete flexural members under monotonic loads. The concrete damage plasticity model (CDP) is used for bridge deck concrete. The nonlinear analysis model is shown in Figure 2.

3.2. Verification of numerical models

In the literature [7], the three-point loading test of the I-beam simple-supported composite girder bridge was carried out. Based on the ABAQUS Standard module, a nonlinear numerical analysis model was established for this test beam. Figure 3 is a comparison of the calculated load-midspan deflection curve of the numerical model with the measured curve. Table 2 shows the comparison of the key stress stages. It can be seen from Table 2 and Figure 3 that the numerical model agrees well with the measured load deflection curve. The accuracy of the numerical model established in this
paper is verified and can be used to analyze the parameters of the twin-I girder steel-concrete composite girder bridge in this project.

| Parameter   | $P_c$/kN | $P_d$/kN | $\delta_1$/mm | $\delta_2$/mm |
|-------------|----------|----------|---------------|---------------|
| Measured values | 264.6    | 434.6    | 12.3          | 110.0         |
| Calculated values | 276.0    | 421.5    | 11.8          | 116.0         |
| Measured / Calculated | 1.043    | 0.970    | 0.969         | 1.050         |

4. Analysis of structural ultimate strength of different bridge spans

In order to study the stability and ultimate bearing capacity of curved steel plate composite girder bridges with different bridge spans, the 35m standard span composite girder bridge with radius of curvature $R=460m$ in real bridge is selected to study full-range mechanical behavior in construction and finished step.

4.1. Comparison of stability at construction step

This paper carried out the elastic stability analysis and nonlinear stability analysis of the structure, and the stability safety factor is used to evaluate the structural stability of different bridge spans. The ratio of the ultimate load to the design load that the structure can withstand before the failure during construction is used to describe the stable and safe reserve of the structure as a whole. The second type of stability safety factor of steel girder in construction stage can be expressed as:

$$\lambda_{cr} = \frac{P_{cr}}{P_d}$$  \hspace{1cm} (2.18)
Table 3. Stability results of construction step of bridge with different bridge spans.

| Number of bridge spans | Radius of curvature /m | Load form | load factor \( \lambda_1 \) | Stable safety factor \( \lambda_{cr} \) | Instability mode |
|------------------------|------------------------|-----------|-----------------|-----------------|-----------------|
| 1                      |                        |           | 3.6             | 3.0             | Wing buckling   |
| 2                      | 460                    | uniform load | 5.6             | 4.5             | Web buckling    |
| 3                      |                        |           | 8.5             | 6.7             | Web buckling    |
| 4                      |                        |           | 8.9             | 7.0             | Web buckling    |
| 5                      |                        |           | 9.2             | 7.2             | Web buckling    |

Table 3 shows the variation of the stability safety factor of the curved composite beam bridge with the number of bridge spans. As the number of bridge spans increases, the stability of the full bridge is gradually improved, and the growth trend is gradually slowing down. Among them, the 3-span structure has a stability safety factor of about 123% compared with the simple-supported curved beam bridge, and the stability of the structure of the three spans and above are almost the same.

4.2. Comparison of ultimate bearing capacity at finished step

On the basis of considering the influence of the construction process on the structural stress state, the ultimate bearing capacity of the combined continuous beam of each bridge span is analyzed. In this paper, according to the road-I class lane load calculation, the uniform load standard value and the concentrated load standard value are calculated by multiplying the lane load to the structural damage, and the whole process stress analysis is carried out to obtain the ultimate bearing capacity of the structure. The loading factor (hereinafter referred to as the live load factor) is used to reflect the ultimate bearing capacity of the structure.

Figure 4 shows that the live load factor of the 35m standard span curve composite beam bridge with 2 spans to 5 spans is close to the ultimate load capacity, indicating that the ultimate load capacity of the bridge is basically the same, and the ultimate deflection of the two spans is the maximum.

5. Analysis of ultimate bearing capacity of structures with different curvature radius

5.1. Comparison of stability at construction step

By changing the radius of curvature \( R \), the influence of the structure on the stability and safety of the structure during the construction process and the ultimate bearing capacity after the bridge was studied. Select \( R=100m, 200m, 460m, 500m, 600m, 800m, 1000m \) and linear bridge for comparative study.

Table 4. Stability results of composite girder bridges with different curvature radius.

| Number of bridge spans | Radius of curvature /m | Load form | load factor \( \lambda_1 \) | Stable safety factor \( \lambda_{cr} \) | Instability mode |
|------------------------|------------------------|-----------|-----------------|-----------------|-----------------|
| 1                      | 100                    |           | 4.8             | 3.8             | Wing buckling   |
| 2                      | 200                    |           | 6.9             | 5.4             | Web buckling    |
| 3                      | 460                    | uniform load | 8.6             | 6.7             | Web buckling    |
| 4                      | 500                    |           | 8.7             | 6.8             | Web buckling    |
| 5                      | 600                    |           | 8.9             | 6.9             | Web buckling    |
| 6                      | 800                    |           | 9.0             | 7.0             | Web buckling    |

It can be seen from Table 4 and Figure 5 that with the increase of the radius of curvature, the stability safety factor of the steel beam increases gradually during the construction phase, and grows faster when \( R=100~500m \), but increases slowly when \( R=600~1000m \). It is relatively gentle, and each beam breaks into a plastic hinge on the side of the outer main girder.
5.2. Comparison of ultimate bearing capacity at finished step

Table 5. Comparison table of live load coefficient of mid-span section of inner and outer main beams with different curvature radius

| Radius of curvature /m | Load form          | Live load factor /$\lambda_2$ | Coefficient ratio Inner/Outer |
|------------------------|--------------------|-------------------------------|------------------------------|
|                        | plastic hinge1/outer girder | plastic hinge2/inner girder |                              |
| 100                    | uniform load       | 6.68                          | 8.37                         | 1.25 |
| 460                    |                     | 7.33                          | 9.57                         | 1.31 |
| 800                    |                     | 8.92                          | 9.61                         | 1.08 |
| Straight bridge        |                     | 9.85                          | 9.85                         | 1.00 |

It can be concluded from Table 5, Figure 6 and Figure 7 that with the increase of curvature radius, the live load factor of the structure after construction of bridges gradually increased, and the growth is faster when $R=100$~$500m$, and above $R=600m$ until the straight bridge the live load coefficient displacement curve is closer, the ultimate bearing capacity changes more gently and shows an upward trend. Due to the coupled action of bending with torsion, the ultimate live load coefficients of the outer and inner main beams are different. The larger the radius, the easier the outer main beam yields and...
the plastic hinge causes the structure to break. As the radius increases, the live load coefficient gradually approaches when the inner and outer main beams are destroyed.

6. Concluding Remarks

(1) The large-scale general finite element program ABAQUS was used to establish a nonlinear numerical analysis model, which can better analyze the whole process of the curved steel plate composite beam and clarify the stability performance and ultimate bearing capacity of the structure.

(2) For the composite beam bridge with different bridge spans, during the construction process, the stability of the three-span structure is the most obvious compared with the simple support structure, and the stability of the three-span and above structures is similar. The ultimate live load system of the post-bridge structure is not sensitive to the number of bridge spans, indicating that the ultimate bearing capacity of the structure is close under the same design conditions, and the stability of the construction process is the control condition of structural safety.

(3) Due to the bending and torsion coupling and the characteristics of the double main beam structure, the ultimate bearing capacity of the structure increases with the increase of the radius. When the radius is less than 460m, the plastic hinge of the outer main beam is generated in advance, the bearing capacity is rapidly reduced. The selection of small radius curved beam bridges should be cautious.

(4) The difference of ratio of the inner and outer live load coefficients can provide the design for the beam height optimization of the same type of structure. For reference, by setting different inner and outer main beam heights, material properties can be fully utilized to achieve economical goals.

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