Analysis of influence factors and stability of concrete-filled steel tube arch bridge

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Abstract. A structural calculation model of a fly-bird-type concrete-filled steel tube arch bridge was established by using large general finite element software. The stability of the bridge during construction and in each working condition was numerically simulated and analysed. Linear elasticity, geometric nonlinearity and material nonlinearity stability safety factors were calculated and their influences on the stability were compared. At the same time, the main influence factors of the fly-bird-type concrete-filled steel tube arch bridge stability are discussed, the influences of the wind bracing number, form and stiffness on the bridge stability are calculated and analysed, and the reasonable values or forms range and the structural stability influencing factors under different value conditions are studied.

1. Introduction

The concrete-filled steel tube (CFST) “Fly-Bird-Type” arch bridge, also called half-through concrete-filled steel tube tied arch bridge, named as its appearance is very similar to bird flies. It is a unique type of concrete-filled steel tube arch bridge, the main span is half-through concrete-filled steel tube arch, both side span is deck-type cantilever half arch, the main span and side span arch foot is fixed to the pier, with tie bar run through the main span and connect two side spans, and balance the thrust for reducing the disadvantages influence to bridge pier and abutment. This kind of bridge has many advantages, such as the structure novel and unique conception, reasonable stress, light and beautiful, long span, low building height, good economic indicator, simple construction technology. The kind of bridge has the feature with both very aesthetic image and a large spanning ability.

“Fly-Bird-Type ” arch bridge has many advantages and developed rapidly in decades, but it is a new type bridge, not very mature and perfect that the structure analysis theory such as structure calculation and stability analysis or engineering technology such as construction and design, so it is very necessary to study stability analysis on it. Based on Wuhan Jianghan river fifth bridge engineering, modeling analysis and discussion of the structure stability on this kind of bridges is obtained in this paper.
2. Engineering examples and finite element modelling

2.1. Engineering general situation

Jianghan river fifth bridge is a bridge across the Han River, in the west of the Third Ring Road in Wuhan City; with 55+240+55 three spans “Fly-Bird-Type” CFST arch bridge, and 27 meters wide. Trial operation is in early 2001.

The main arch rib: 240 meters clear span, 1/5 the ratio of rise to span, catenary arch axis, arch axis coefficient \( m = 1.5 \). The main span camber values is 0.4 meters in arch crown, the arch axis is still catenary after camber set, and the arch axis coefficient \( m = 1.4 \). The main arch ring is formed by the truss structure, composed of concrete filled steel tube chord and steel tube web chord, the arch rib is 4.5 meters high, each lower chord and upper chord is formed by two steel tube side by side that with 1 meters in diameter, 14 mm wall thickness, C50 concrete filled in, connected with 12 mm thick batten plate filled in C50 concrete, the web chord is hollow steel tube with 500 mm diameter and 10 mm wall thickness. The two arch ribs are provided with seven K shaped space lattice bracing to ensure the lateral stability of the main arch ribs.

Side span: 55 m half span half arch structure, catenary arch axis, arch axis coefficient \( m = 1.9 \). the solid ribbed reinforced concrete section used, each rib is 3.5 meters high, 2.4 meters wide, used to provide the tie bar anchorage and balance the main thrust of arch. Reinforced concrete circular columns with 800 mm diameter set on the main arch; solid reinforced concrete beam is arranged at the end part in side span to provide weight.

In addition, the hanger rods are 32 pairs, also 64, using parallel wire cable finished cable standard strength of 1570 MPa, 6 meters the longitudinal distance. The tie rod are the prestressed steel strand finished cable using low relaxation steel strand standard strength of 1860 MPa and 15.24 diameter, anchored on the side span end through the main arch rib.

2.2. Finite element modeling

Concrete filled steel tube is a combinational material formed by concrete pouring in steel tube, although it is composed of steel tube and concrete the two kinds of materials, due to the interaction and close connection of two kinds of material, the working performance have taken place great changes. It is actual difficult that the simulation carried on fully reality conformation. At present, there are two main academic simulation method of single material model and the double material model, the single material model is divided into equivalent material model and the unified theory model. single material model is used to simulate the section properties of concrete filled steel tube, the CFST considered as a material, not only to distinguish between steel and concrete, the load carrying capacity is determined by the all component geometric characteristics and combination performance.

Jianghan river fifth bridge main arch rib is concrete filled steel tube material, on the analysis of linear elastic and geometric nonlinearity, the concrete and steel tube viewed as a unit to calculate, the finite element software MIDAS is used to establish the finite element model, as shown in figure 1. On the analysis of the materials nonlinear stability, the main arch rib using unified theory model of three line constitutive relation, that the whole process is divided into elastic, elastic-plastic and enhancement three stages, the finite element software ANSYS in modeling is calculated as shown in figure 2.

![Figure 1. MIDAS bridge spatial model.](image-url)
3. construction stability Analysis

According to the Jianghan river fifth bridge construction design and actual construction project, the construction stage is divided into 14 main construction conditions.

Elastic stability calculation, geometric nonlinear stability calculation and material nonlinear stability calculation are for each construction stage carried out through the MIDAS, ANSYS full bridge finite element model. The following points can be obtained.

(1) the elastic stability safety coefficient in each construction stage is greater than 6, meet the requirements of that the first stability safety coefficient is greater than 4, material and geometrical nonlinear stability safety coefficients were greater than 2.6, meet the requirements of that the second stability safety coefficient is greater than 2.5 (the second stability safety coefficient must be greater than 2 in some criterion).

(2) the maximum elastic, geometric nonlinear, material nonlinear stability safety coefficient occurred in the condition 1 of construction stage, while the main arch rib steel tube closure into hingeless arch, its minimum value occurred in the condition 5 of construction stage, while concrete casted in the main arch rib the lower chord one steel tube, concrete strength has not yet reached, stability safety reserves is minimum, material nonlinear safety coefficient is merely 2.6.

(3) from the whole process of construction, construction stage instability easily emerged is the stability safety coefficient is low, mainly concentrated in construction stage of the concrete cast and bridge deck system installation, corresponding construction conditions 4 to 9, 13 and 14 in table 1. In the concrete cast stage, the concrete cast and has not yet reached the strength, concrete is taken as load, stability safety factor is not high; In the bridge deck system installed stage, the new bridge dead load increased, he bridge deck system is considered as deck load, the stability safety factor is not high.

(4) compared with elastic, geometric nonlinear, material nonlinear stability safety coefficient, the geometric nonlinear stability safety coefficient changed little relative the first stability safety coefficient, considering the geometric nonlinearity, the stability coefficient declined between 3.3% to 9.4% compared to elasticity values, so geometric nonlinear analysis less affected bridge construction stage stability. Material nonlinear stability safety coefficient changed more relative the first stability safety coefficient, considering the material nonlinear, the stability coefficient declined 60% to 86%, so material nonlinear analysis heavily affected bridge construction stage stability. Therefore, the stability analysis must include the influence of nonlinear factors to ensure the construction safety.

(5) For comparison with unstability state in each construction stage, the bridge unstability state in each construction stage is mainly spatial transverse unstability, More unstability state of the construction stage is the out of the plane.

4. The completed bridge stability analysis

For arch bridge in urban, constant load weight accounted for a larger proportion of the whole load, and with the increase of span, the constant load accounted for larger proportion. Therefore the live load layouts on Jianghan river fifth bridge calculation models, based on strengthening adverse circumstances of the bridge section caused by the self-weight load. The maximum internal force of arch rib each section is calculated according to the bridge section the worst-case loading of bending moment influence line. Stability analysis is carried out for 4 load conditions on the Jianghan river fifth bridge calculation models.

Completed bridge load condition 1: constant load, secondary constant load and vehicle load-on full span eccentrically.
Completed bridge load condition 2: constant load, secondary constant load and vehicle load-on half span eccentrically.

Completed bridge load condition 3: constant load, secondary constant load and vehicle load-on reverse symmetrical eccentrically.

Completed bridge load condition 4: constant load, secondary constant load and vehicle load-on full span symmetrically.

Elastic stability, geometric nonlinear stability and material nonlinearity stability calculated under four load conditions of completed bridge, and then obtain the stability safety coefficient, which is shown in Table 1.

| Completion conditions number | Elastic stability safety coefficient | Geometric nonlinear stability safety coefficient | Material nonlinearity stability safety coefficient | Unstability mode |
|-----------------------------|-------------------------------------|-----------------------------------------------|--------------------------------------------------|------------------|
| 1                           | 9.92                                | 9.03                                          | 3.9                                              | reverse symmetrical transverse instability |
| 2                           | 10.20                               | 9.18                                          | 4.1                                              | reverse symmetrical transverse instability |
| 3                           | 9.92                                | 9.13                                          | 4.3                                              | reverse symmetrical transverse instability |
| 4                           | 9.40                                | 8.06                                          | 2.8                                              | reverse symmetrical transverse instability |

According to table 1, considering the geometric nonlinearity, the completed bridge stability safety coefficient of Jianghan river fifth bridge dropped slightly relative to linear elastic, about 7%-15%, so the geometric nonlinearity factors have a certain impact on the bridge stability, but the influence range is not big. Considering the material nonlinear factors, stability safety coefficient dropped sharply relative to linear elastic, decreased by 56%-71%, so the material nonlinear factors have a significant impact on the stability of the whole bridge. Therefore, on the analysis of the stability in the actual project, the choice of reasonable constitutive relation model and the effect of geometric nonlinear, material nonlinear are also considered. In addition, the instability mode is the entire out plane buckling, as shown in figure 3.

![Figure 3. Material nonlinear unstability buckling mode on completed bridge.](image)

5. Analysis of the stability influencing factors

Based on the Jianghan river fifth bridge MIDAS model, using the method of varying finite element model parameter, such as the wind bracing stiffness, numbers, form, etc., it is compared and discussed that the influence of these factors on the stability of concrete-filled steel tube “Fly-Bird-Type” arch bridge structure.

The Jianghan river fifth bridge wind bracing is space truss, the wind bracing rod, brace and inclined strut are all empty steel tube. The load conditions is constant load and vehicle load-on full span.
eccentrically to analysis the influence of these factors on the stability of concrete-filled steel tube “Fly-Bird-Type ” arch bridge structure.

5.1. The influence of wind bracing number
At between double ribs of the main arch ribs, “straight wind bracing” is set, the number is 3, 5, 7, 13 respectively, the transverse stability coefficient is calculated respectively. The transverse stability coefficient with different number wind bracing is shown in table 2, the influence of the wind bracing numbers to Jianghan river fifth bridge structure transverse stability is obvious. The more the wind bracing number, the stability of bridge is higher.

| wind bracing number | 3   | 5   | 7   | 13  |
|---------------------|-----|-----|-----|-----|
| stability coefficient| 2.64| 2.88| 2.99| 3.19|

5.2. The influence of wind bracing form
Concrete filled steel tube arch bridge wind bracing mainly used the form of " straight ", "K" , "rice" and" X ". In the discussion of wind bracing form influence on stability, the model with 7 wind bracing number is selected as the reference model, the stability coefficient are compared and calculated respectively while the “straight wind bracing” transform for "K" or" rice " accordingly, In order to analyze the influence of wind bracing form on the transverse stability. The stability coefficient calculated is shown in table 3.

| wind bracing form                                              | stability coefficient | unstability mode          |
|---------------------------------------------------------------|-----------------------|----------------------------|
| reference model: 7 " straight "                              | 2.99                  | single wave symmetry       |
| 1 "rice" at arch crown, other 6 "straight"                    | 3.12                  | single wave symmetry       |
| 1 "straight" at arch crown, other 6 " K "                     | 6.94                  | single wave reverse symmetry|
| 1 "rice" at arch crown, other 6 " K "                         | 9.92                  | single wave reverse symmetry|

Through comparing the calculated stability coefficient with different wind bracing form, the influence of the wind bracing form to transverse stability is obvious. The main difference of "straight", "K", "rice" and "X" is incline rods number, the form of retaining incline rods in wind bracing can greatly improve the structure transverse stability.

5.3. The influence of wind bracing stiffness
In addition to the influence of wind bracing number and form on concrete-filled steel tube “Fly-Bird-Type” arch bridge structure; the stiffness influence cannot be ignored. The stiffness changed by changing the wind bracing section size, the linear elastic stability safety coefficient with different wind bracing stiffness calculated, as shown in table 4.

| wind bracing stiffness | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 |
|------------------------|-----|-----|-----|-----|-----|
| stability coefficient  | 9.08| 9.26| 9.98| 10.68| 11.29|

Comparative analysis of stability safety coefficient of different wind bracing stiffness, the bridge stability is strengthening with the wind bracing stiffness increasing, and the relationship between linear elastic stability coefficient and stiffness variation is approximately linear.
6. Conclusion

The following conclusions can be drawn from the calculation.

1. The stability safety coefficient of the instance model meets the requirement of standard. The Jianghan river fifth bridge the first stability safety coefficient in each construction stage and completed stage is greater than 6, meet the requirements of that the first stability safety coefficient is greater than 4. Material and geometrical nonlinear stability safety coefficients were greater than 2.6, meet the requirements of that the second stability safety coefficient is greater than 2.5 or 2.

2. Both in the construction and completed stage, The influence of nonlinear factors on concrete-filled steel tube arch bridge structure stability is considerable, in which, geometric nonlinear analysis less affected bridge construction stage stability, material nonlinear analysis heavily affected, the material nonlinear stability coefficient is several times of elastic stability coefficient. The results linear elastic stability analysis of this kind of bridge is insecure.

3. In the whole construction process, low the stability safety coefficient mainly concentrated in construction stage of the concrete cast and bridge deck system installation, at this stage this kind of bridge stability problem should be highly concerned about.

4. Unstability mode of long span concrete-filled steel tube “Fly-Bird-Type” arch bridge structure is mainly spatial transverse unstability, the effect of spatial transverse stiffness on stability cannot be ignored. In addition, for the load of this kind of bridge stability, the weight is one of the main loads.

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