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Parameter Sensitivity Study of Ultimate Bearing Capacity of Long-span Steel Box Truss Arch Bridge

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Abstract: The ultimate bearing capacity is an important means of evaluate the performance of bridge safety. So it is significant important in the practical engineering to study its influencing factors of ultimate bearing capacity. The influencing factors of ultimate bearing capacity of the structure are analyzed using the spatial finite element model of a Yangtze River Highway Brige. The results show that the in-plane intial geometric defects can't decrease significanly ultimate bearing capacity, while the out-plane intial geometric defects decrease significanly ultimate bearing capacity. The material strength cause ultimate bearing capacity of the structures to increase in proportion. The temperature have little influence on ultimate bearing capacity of the bridge.

Keywords: Steel truss arch; Ultimate bearing capacity; Finite element method; Influencing factor; Plastichinge; Parameter sensitivity study

1. Introduction

Steel box truss arch bridge, with its light weight, large span capacity, high bearing capacity and high degree of assembly, has been applied more and more widely to practical engineering.

In recent years, along with the development of high strength materials and thin-walled structures, the integral and local rigidity decrease significantly. Stability problem is becoming more and more important. For a long time, a series of studies on the stability problem of arch bridge have been carried out by many scholars. But compared with steel box arch bridge, studies on its influencing factors of steel box truss arch bridge are less. The arch rib of steel box truss arch bridge mainly bear the axial pressure and has higher axial compression ration, so it's easier to come into ultimate bearing capacity than the steel box arch bridge. Therefore, it's very necessary to study the influencing factors of ultimate bearing capacity of steel box truss arch bridge.

Based on the point, Further analysis on the fluencing factors of ultimate bearing capacity of long-span steel box truss arch bridge are conducted in this paper. Combining the structure and stress characteristics of the bridge, the saptial finite element model of the Yangtze River Highway Brige was created firstly. Subsequently, the analysis offluencing factors of ultimate bearing capacity are analyzed in detail using the spatial finite element model. Through the analysis, both to provide technical guidance for the smooth implemention of the bridge, also for the further reference for the design of similar bridges.

2. The Theory of Ultimate Bearing Capacity

It is the singular point which is also called the critical point on the equilibrium path that leads to the instability of the structure. The structural instability includes branch point instability and extreme point instability.

The branch point instability is only fits for ideal structure. The actual structure has some initial unavoidable defect because of manufacture and installation. The structure generates displacement along the instability direction when the external load takes effect. The displacement inevitably has some effects on the balance state of the structure. It is named the second kind linear elastic instability which has considered the influence of structure large displacement. The balance equation of the U.L method incremental of the structure can be expressed as:

$$\left([K_0]+[K_s]\right)\{\Delta d\}=\{\Delta F\} \tag{1}$$

In the equations, $[K_0]$ represent elastic stiffness matrix, $[K_s]$ initial stress stiffness matrix, $\{\Delta d\}$ displacement increment matrix, $\{\Delta F\}$ load increment matrix, $[K_0]$ and $[K_s]$ are functions of the displacements $\{d\}$.

From a mechanical perspective, the above only assumes that the material is infinite flexibility. The critical load of the second kind linear elastic instability approaches to the critical load of the branch point instability. Some members have reached its ultimate strength before the load. The essence of analysis of the second kind instability is the progress which considers the influence which the geometric nonlinearity and material nonlinearity cause, solves the balance equation and finds its ultimate load. Curve of total process load-displacement can be obtained when the structure is loaded. The balance equation of the U.L method incremental of the whole structure is:

$$\left([K]_0+[K]_s+[K]_L\right)\{\Delta d\}=\{\Delta F\} \qquad (2)$$

In the equations, $[K_0]$, $[K_s]$, $[K_L]$ represent elastic stiffness matrix, initial stress stiffness matrix and initial displacement stiffness matrix respectively when the time t is 0.

3. The Analytical Method of Ultimate Bearing Capacity

3.1. General engineering situation

The design scheme of the Yangtze River Highway Brige proposed to be built is half-through steel box truss non-hinge arch bridge with a main span of 519m.The radial height of cross-section on the top of arch is 12m,and the radial height of it on the foot of arch is 14m. The two main trusses are arranged parallelly with a center-to-center distance between them of 25.3m.The arch rise of the bridge is 12.7m ,and the rise-span ratio is 1/4.The arch-axis coefficient value of catenary arch is 2.0.The bridge deck with a full width of 27.3m are composed of precast bridge decks and wet-joints. There are 27 pair of suspenders arranged parallelly between the arch rib and bridge deck. The longitudinal distance of every two suspenders is 12m.

The following figure.1 is the general arrangement drawing of the Yangtze River Highway Brige.

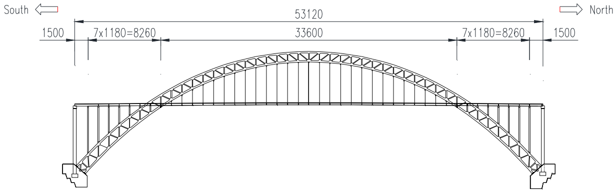

Figure 1. The general arrangement drawing of the Yangtze River Highway Brige(cm)

3.2. The spatial finite element model

According to the design drawings, the spatial finite element model of the Yangtze River Highway Bridge was built by large software Midas/Civil especially suitable for bridge engineering. The analysis on the influencing factors of ultimate bearing capacity are analyzed in detail using the spatial finite element model. The main arch ring, longitudinal bracings, enhanced crossbeams, spandrel structure and vertical and horizontal beams are simulated by spatial finite beam elements. The suspenders are simulated by spatial finite truss elements and the bridge decks are simulated by spatial finite plate elements. The secondary dead load from bridge deck pavement, sidewalk and crash barrier are replaced by equivalent load. The boundaryconditions of model are arranged according to specific location of bearing and actual constraint conditions. Shared nodes are used to connect the precast bridge decks with the vertical and horizontal beams. There are 3585 beam element,54 truss element,1440 plate element and 2725 nodes. The spatial finite element model of the Yangtze River Highway Brige is shown in figure.2.

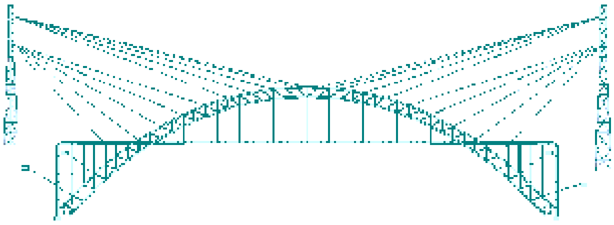

Figure 2. The spatial finite element model of the Yangtze River Highway Brige

3.3. Basic assumption

(1) The pushover function of the Midas/Civil software is used to analyze the ultimate bearing capacity of the bridge in the paper. The material nonlinearity property is realized by setting plastic hinge to spatial beam element section. Plastic hinge is defined by the relationship between the moment and the curvature ratio. Yield surface is automatically calculated through the section and the material property in the software. The yield stress of the steel used in the main truss is s_y=370MPa .The yield stress of the steel used in the bridge floor system and the brace system is s_y=345MPa .The yield stress of the high strength steel rope used in the bridge is s_y=1860MPa .According to the mechanics characteristic of the arch, multi-axis hinge which considers the axis force and the moment simultaneously is used only in boom of the arch rib and spandrel members.

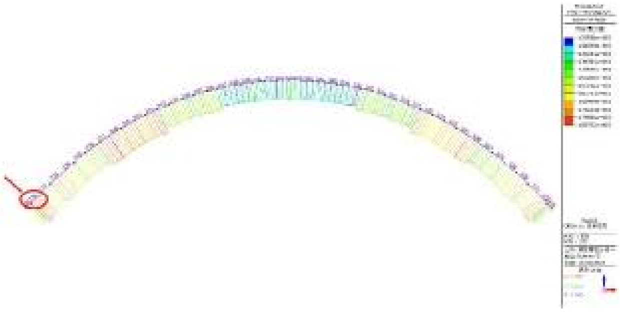

Figure 3. The schematic diagram of control member on ultimate bearing load

(2) To define the worst-case load method of the live load, we need to build the finite element model of the whole bridge and then start the analysis of the moving loads.

The control member which can affect the ultimate bearing capacity of the whole bridge can be determined by checking the stress distribution of the boom of the arch rib. Start the moving load tracker, find the distribution of the moving load when the control member works under the worst-case internal force state and convert the moving load to the static load. Then define the load case and treat it as the worst-case load method of the live load when starting the analysis of the ultimate bearing capacity of the bridge.

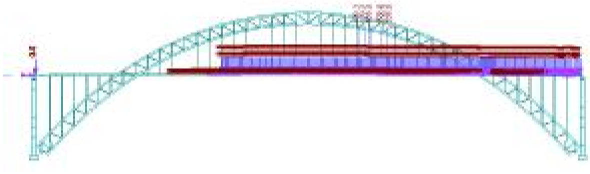

Figure 4. The worst-case load method of the live load

(3) Because the arch does not have uniform dead load density, in the paper, critical collapsing load under the elastic state is defined as $P_{cy}=l_{cr}P_q+P_g$ 。 For the analysis of the ultimate bearing capacity of a bridge, $P_{cy}=l_{cr}P_q+P_g$ is just used. In the equations, P_g represents the dead weight of the structure(including secondary dead load), P_q represents the live load(including vehicle load and pedestrian load), l_{cr} is the multiple of load used when it reaches the ultimate bearing load.

4. The Analysis of Parameter Sensitivity for Ultimate Bearing Capacity

There are many factors affecting the ultimate bearing capacity of the structure for long-span steel box truss arch bridge. It's necessary to analyze the influencing factors of ultimate bearing capacity combining to the characters of structure. Through the analysis, both to provide technical guidance for the smooth implemention of the bridge, also for the futuer reference for the design of similar bridges

4.1. Effect of out-plane geometric initial defect

When in the previous design and analysis, the bridge is regarded as a structure composed of perfect members. But in practical engineering, the impections of structural members can emerge inevitably when the members are manufactured in the factory, transported on the way and installed on the construction site. The defects can be controlled to a small degree, but they can't be avoided completely. The structual defects may decrease significantly the ultimate bearing capacity of sensitive structure. Because of the complicated structure for long-span steel box truss arch bridge, It's more necessary to study the influence of structural defects on tne ultimate bearing capacity. The vector characteristics buckling shape is closest to the predicted value of the actual buckling mode. It can be the gist to exert geometric intial imperfections. Therefore, this project in consideration of initial geometric imperfection, try using eigenvector method to exert initial geometric imperfections to the structure.

Through the analysis of the linear elastic stability of large-span steel truss arch bridge, the first order buckling mode (out-plane lowest order buckling mode) can be obtained. The initial lateral deviation is the deviation between the actual coordinates of arch rib and the coordinates of ideal perfect arch rib. It can be obtained through multiply between lateral displacement of the first order instability mode in arch numerical model and the same proportion factor β. The proportion factor β can be calculated through the following formula:

$$b=\frac{Amplitude\ of\ the\ out-plane\ biggest\ defect?}{Maximum\ lateral\ displacement\ of\ first-order\ buckling\ mode}$$

During the modeling of the arch bridge, the actual coordinates of arch structure equal to the sum of the coordinates of ideal perfect arch rib and the initial lateral deviation. The finite element mode in consideration of out-plane geometric initial defects is modeled according to above method. During the specific analysis and calculation. The amplitude of defects take respectively the calculated span of 1/2500,1/2000,1/1500,1/1000,1/500.The geometric nonlinearity and material nonlinearity are talked into consideration in the analysis. The ultimate bearing capacity and influence law are studied through loading step by step.

Table 1. The effect of out-plane geometric intial defects on ultimate bearing capacity

Amplitude	L/2500	L/2000	L/1500	L/1000	L/500
Safety cofficient	13.15	13.15	13.15	13.15	13.15

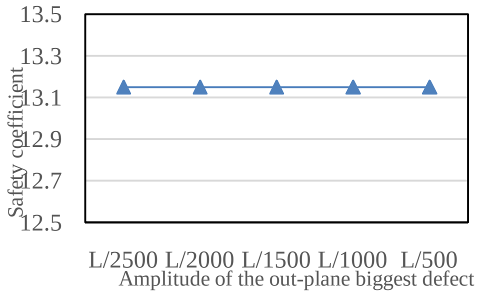

Figure 5. The influencecurve diagram of out-plane geometric intial defect on ultimate bearing capacity

The results as showed in table.1 and figure.5 illustrates that the out-plane geometric initai imperfections have little influence on the ultimate bearing capacity when the out-plane lowest order instability mode is regarded as the distribution modes of defects. The ultimate bearing capacity of the brdige is almost unchanged as the amplitude of the defect changes.

4.2. Effect of in-plane geometric initial defect

Through the analysis of the linear elastic stability of large-span steel truss arch bridge, the third order buckling mode (in-plane lowest order buckling mode) can be obtained. The initial lateral deviation is the deviation between the actual coordinates of arch rib and the coordinates of ideal perfect arch rib. It can be obtained through multiply between vertical displacement of the third order instability mode in arch numerical model and the same proportion factor β. The proportion factor β can be calculated through the following formula:

$$b=\frac{Amplitude\ of\ \ the\ in-plane\ biggest\ defect?}{Maximum\ vertical\ displacement\ of\ \ first-order\ buckling\ mode}$$

During the modeling of the arch bridge, the actual coordinates of arch structure equal to the sum of the coordinates of ideal perfect arch rib and the initial lateral deviation. The finite element mode in cosideration of out-plane geometric initial defects is modeled according to above method. During the specific analysis and calculation. The amplitude of defects take respectively the calculated span of 1/2500,1/2000,1/1500,1/1000,1/500.The geometric nonlinearity and material nonlinearity are taked into consideration in the analysis. The ultimate bearing capacity and influence law are studied through loading step by step.

Table 2. The effect of in-plane geometric intial defects on ultimate bearing capacity

Amplitude	L/2500	L/2000	L/1500	L/1000	L/500
Safety coefficient	12.90	12.85	12.75	12.60	11.90

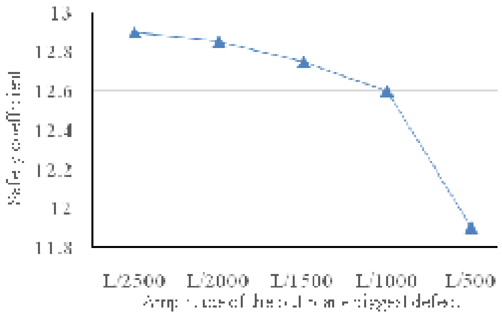

Figure 6. The influencecurve diagram of in-plane geometric intial defect on ultimate bearing capacity

The results as showed in table.5 and figure.6 illustrates that the in-plane geometric initai imperfections have a significant influence on the ultimate bearing capacity when the in-plane lowest order instability mode is regarded as the distribution modes of defects. The ultimate bearing capacity of the bridge decrease significantly as the amplitude of the defect increase.

Through above analysis results, It conclude that the out-plane geometric initial defects have little influence on the ultimate bearing capacity. The influence on ultimate bearing capacity from out-plane geometric intial defects exceed significantly that of in-plane geometric initial defects.

4.3. Effect of steel yield strength

Through consulting relevant research literature, we can draw a conclusion that material nonlinearity is a decisive factor to influence ultimate bearing capacity of steel box truss arch bridge. Changing the strength of steel will directly lead to changes in the yield strength of steel, while the yield strength is an important factor affecting the material nonlinearity. So for long-span steel box truss arch bridge, the steel intensity change is bound to have a significant impact on ultimate bearing capacity.

Now the finite element model with foregoing load conditions is analyzed under 4 different situation of steel yield strength as listed below:

Situation 1:the chordmember of the main arch rib using Q295,the longitudinal bracings and web member of the main rib using Q235,the segment of the arch springings using Q345.

Situation 2:the chordmember of the main arch rib using Q345,the longitudinal bracings and web member of the main rib using Q295,the segment of the arch springings using Q370.

Situation 3:the chordmember of the main arch rib using Q370,the longitudinal bracings and web member of the main rib using Q345,the segment of the arch springings using Q390.

Situation 4:the chordmember of the main arch rib using Q390,the longitudinal bracings and web member of the main rib using Q370,the segment of the arch springings using Q420.

Table 3. The effect of steel yield strength on ultimate bearing capacity

Strength situation	Situation 1	Situation 2	Situation 3	Situation 4
Safety coefficient	10.05	12.75	13.24	14.92

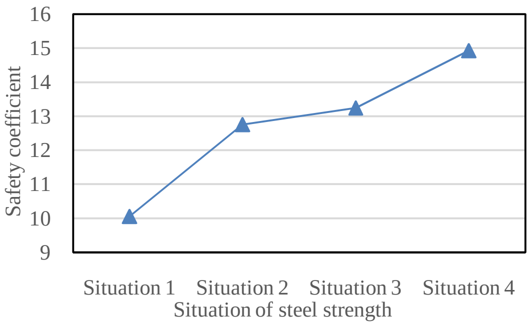

Figure 7. The influencecurve diagram of steel yield strength on ultimate bearing capacity

The above computed results illustrate that the steel yield strength increase significantly the ultimate bearing capacity of bridge. The steel yield strength of the main truss chords changes from 345MPa to 390MPa,and the ultimate bearing capacity of bridge increases 48.4%,corresponding load safety factor improving 57.0%,almost equal proportions of the increase. Thus in structure design, different types of steel can be chosen in terms of the size of force that the bridge bears. It makes the structure not only meet the demand of security, but also achieve the functional requirements of economical efficiency. In a word, the material strength is a critical factor to affect the ultimate bearing capacity of long-span steel box truss arch bridge.

4.4. Effect of temperature

For a more comprehensive study of the influence on ultimate bearing capacity of long-span steel box truss arch bridge, the seasonal temperature difference has been taked into account in the study. The overall impact of seasonal temperature differences including temperature rise and temperature drop is analyzed in the paper. While the double nonlinear effect is also considered and the live load is arranged according to the most unfavorable load conditions. The load safety coefficient under various temperature difference is shown in table.4 and figure.8.

Table 4. The effect of temperature on ultimate bearing capacity

Temperature exchange value	Safety coefficient
-30	13.397
-20	13.328
-10	13.259
0	13.264
10	13.225
20	13.242
30	13.189

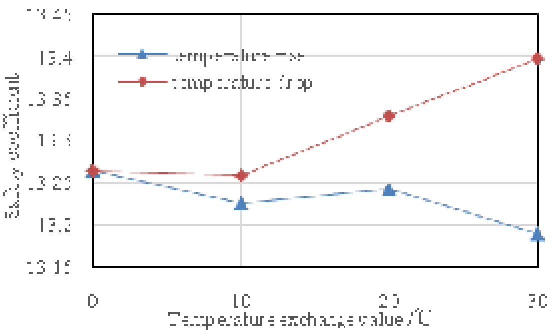

Figure 8. The influencecurvediagram of temperature on ultimate bearing capacity

The table 4 and figure 8 show that The temperature have little influence on ultimate bearing capacity of the bridge. When the temperature rise or temperature drop reach 30℃,the safety coefficien of ultimate bearing capacity change less than 1%.The general trend is that the temperature drop in favor of the structures to withstand loads, temperature rise is not conducive to the structure to withstand other loads.

5. Conclusion

Through the calculation and analysis, this paper gives the following conclusions:

The influence of initial geometric defects on ultimate bearing capacity is study in the paper. The results illustrate that the in-plane intial geometric defects can't decrease significanly ultimate bearing capacity, while the out-plane intial geometric defects decrease significanly ultimate bearing capacity.

This paper analyzes the impact of the steel yield strength and temperature on the ultimate bearing capacity of the bridge, the results show that The material strength cause ultimate bearing capacity of the strectures to increase in proportion. The temperature have little influence on ultimate bearing capacity of the bridge. The general trend is that the temperature drop in favor of the structures to withstand loads, temperature rise is not conducive to the structure to withstand other loads.

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