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ANALYSIS OF ULTIMATE BEARING CAPACITY FOR LONG-SPAN STEEL BOX TRUSS ARCH BRIDGE

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Abstract—With the increase of span length of steel box truss arch bridge,the problem of nonlinear effect becomes even more promient.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 the ultimate bearing capacity of long-span half-through steel box truss arch bridge.A Yangtze River Highway Brige is a long-span half-through steel box truss arch bridge with a main span 519 m.The ultimate bearing capacity of the structure are analyzed using the spatial finite element model.The results show that the influence of nonlinearities must be considered in the analysis of ultimate bearing capacity.
Keywords—steel box truss arch;ultimate bearing capacity;finite element method;plastic hinge.

With the increase of steel production,steel arch bridge has been developed rapidly.The bridge span reach new peak frequently.Nowadays it has been a common bridge structure form which was widely applied to highway bridge.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.

Arch rib is a planar curved rod system mainly bearing axial pressure,the structure reaches ultimate bearing capacity and damage mainly due to the following two conditions:1. Under load,the bridge lost its stability because of its own deficiency of stiffness,that is linear or nonlinear elastic buckling question;2. Under load,the stiffness degradation caused by strength problem rusults in instability,that is elastic-plastic stability or ultimate bearing capacity question.

Nowadays,the study mostly focus on the first situation in the practical engineering.In general,the analysis is made based on elastic theory.It's needed to adopt greater load safety coefficient stability checking in design.As for long-span bridges,the material may be in elastic-plastic phase when the bridge damage due to instability.Now the load safety coefficient calculated according to elastic theory exceed real value.So it's essential to analyze ultimate bearing capacity.

For a long time, a series of studies on the ultimate bearing capacity problem of steel arch bridge have been carried out by many scholars.But compared with steel box arch bridge,studies on ultimate bearing capacity problem 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 yield phase than the steel box arch bridge.Therefore,it's very necessary to study the ultimate bearing capacity of steel box truss arch bridge.

Based on the point,Further analysis on the ultimate bearing capacity of long-span half-through 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 on the 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 futuer reference for the design of similar bridges.

I. THE THEORY OF STRUCTURAL STABILITY AND 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.

It has been assumed that the structure stays in the range of small elastic deformation when it reaches the branch point instability or critical load.It's also the time that the internal force is proportional to the external load.Now the balance of the structure emerges branch.The balance equation of the current structure is:

$$\left(\left[K_0\right]+\lambda\left[K_\sigma\right]\right)\left\{\delta\right\}=0 \qquad (1)$$

The critical load is $P_{cr}=\lambda_{min}\cdot P_0$,which can be obtained by solving the characteristic equations.The problem of branch point instability is simple and explicit which equals to solving eigenvalue in mathematics.It can be easily solved and improve the efficiency of stability analysis.The critical load can represent the upper limit of the second kind of stability approximately in the structure.In conclusion, The branch point instability occupies a very important position in the theory analysis.

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:

$$\left(\left[K_0\right]+\left[K_\sigma\right]\right)\left\{\Delta\delta\right\}=\left\{\Delta F\right\} \qquad (2)$$

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

From a mechanical perspective,the above only considers geometric nonlinearity and the initial defect.It 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.Load increment method usually be used to solve the problems of critical point instability.The balance equation of the U.L method incremental of the whole structure is:

$$\left([K]_0+[K]_\sigma+[K]_{\mathrm{L}}\right)\{\Delta\delta\}=\{\Delta F\} \qquad (3)$$

In the equations, $[K_0],[K_\sigma],[K_{\mathrm{L}}]$ represent elastic stiffness matrix,initial stress stiffness matrix and initial displacement stiffness matrix respectively when the time t is 0.

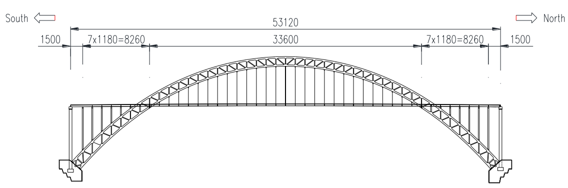
II. ANALYSIS OF ULTIMATE BEARING CAPACITY FOR THE BRIDGE

A. General engineering situation

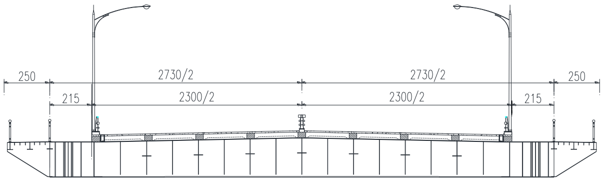
The design scheme of the Yangtze River Highway Brige proposed to be built is half-through steel box truss non-hinge arch bridge wih a mian span of 519m.The arch rib is a spatial structure with variable cross-section truss.The radial height of cross-section on the top of arch is 12m, and the radial height 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.They are composed of steel box girders of equal section and steel I-shaped beams with vertical stiffeners.The combined welding and integral joint are applied to joint connection.The distance between the bottom chord of the truss and the upper chord of it is 508m.The arch rise of the bridge is 12.7m ,and the rise-span ratio is 1/4.

Above the bridge deck,the diamond-longitudinal bracings are arranged among the upper plane of the main arch ring.There are no longitudinal bracings arranged among the lower plane of the main arch ring.Besides,the K-shaped longitudinal bracings are arranged on the upper and lower plane of the main arch ring below the bridge deck arranged.Enhanced crossbeams are set on the juncture of the arch rib and bridge deck.The arch bridge axis utilize catenary,and the arch-axis coefficient value of catenary arch is 2.0. The steel bent structure is utilized to form spandrel structure.The bridge deck with a full width of 27.3m are composed of precast bridge decks and wet-joints.The bridge is a part of bi directional and four lane highway.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.2 is the general arrangement drawing of the Yangtze River Highway Brige .It will be a non-hinge arch bridge with the largest span in the world after completion.



（a）elevation



（b）profile

Fig. 1 Figure of the general arrangement drawing of theYangtze River Highway Brige (cm)

B. 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 linear elastic stability and fluencing factors of stability are analyzed in detail using the spatial finite element model.

In the model,the main arch ring,longitudinal bracings,enhanced crossbeams,spandrel structure and vertical and horizontal beams are simulated by spatial finite beam elements.The impact of stiffening ribs has been taked fully into account when the Cross section properties are defined. 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 boundary conditions of model are arranged according to specific location of bearing and actual constraint conditions. The connection between bridge deck and spandrel structure are simulated by node coupling The arch springings of both sides have fixed constraints.Shared nodes are used to connect the precast bridge decks with the vertical and horizontal beams.When the actual bridge structure is dispersed into spatial finite element model,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.

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

C. 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

σ_y=370MPa .The yield stress of the steel used in the bridge floor system and the brace system is σ_y=345MPa .The yield stress of the high strength steel rope used in the bridge is σ_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.

(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.

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

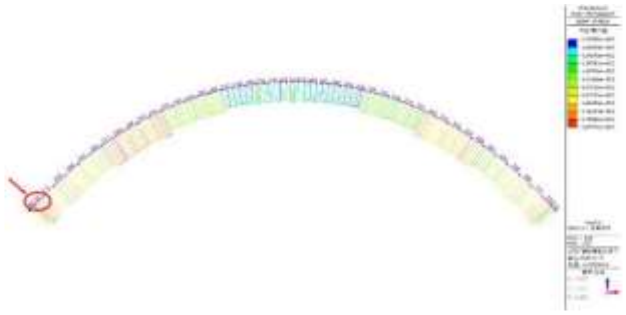


Fig. 3 The schematic diagram of control member on ultimate bearing load

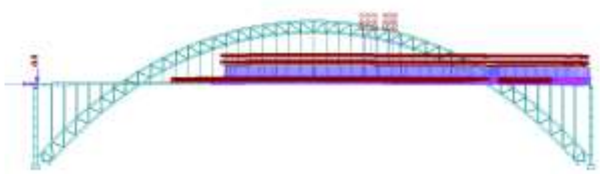


Fig. 4. The worst-case load method of the live load

D. The analysis of linear elastic stability

According to the theory of linear elastic stability,the linear elastic stability is analyzed firstly to study the ultimate bearing capacity of the bridge under dead load and live load in operation phase.The dead load includes weight of the structure and secondary dead load.The live load is arranged in accordance with aforementioned the worst-case load method.

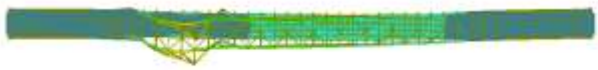
By calculation,based on the definition of the ultimate bearing capacity safety coefficient,the safety coefficient of first three buckling and the modal characteristics of the aforementioned conditions of the bridge are shown in Table 1.Due to space limitations, only the first three bridge buckling mode are listed in Figure 5.

Table 1 The load safety coefficient and modal characteristic of the first three orders instability

Order	Safety coefficient	The modal characteristic of instability
1	92.7	Local instabilityof lower chords
2	112.9	Local instabilityof lower chords
3	124.0	Local instabilityof lower chords

(a) The first-order instability mode

(b) The second-order instability mode



(c) The third-order instability mode

Fig. 5 The first three orders instability modes under the linear elastic state

By analyzing the information of table 1,We can see that the lowest order instability mode of the Yangtze River Highway Bridge in various operating conditions is out-plane instability or local fishbone-like instability of chords.While the first-order safety coefficient meet the requirement of design and standard.

The characteristics of all-order instability mode as shown in fig.5 illustrate that the kind of long-span half-through steel box truss arch bridge appear out-plane instability relatively easily and most likely to occur in the arch rib without longitudinal bracings.

E. The analysis of ultimate bearing capacity

Because the geometric nonlinearity,material nonlinearity and initial geometric defects are not taked into consideration for the method of linear elastic stability analysis,the critical load almost only represent the upper limit of the second kind of stability approximately in the structure.So it’s necessary to analyze elastic-plastic stability considering geometric nonlinearity and material nonlinearity for obtaining ultimate bearing capacity.The completed bridge phase is used to make a analysis of ultimate bearing capacity.The initial dead load of the structure (including the dead weight and the secondary dead load) is loaded on the bridge,then the live load (including vehicle load and pedestrian load) is loaded step-by-step until the bridge achieve its ultimate bearing capacity.

The curve of load-displacement of control point is shown in figure.6.Because the ultimate load is definited as 50 times live load,the actual load safety coefficient is $\lambda_{cr}=50\times0.28=14$.

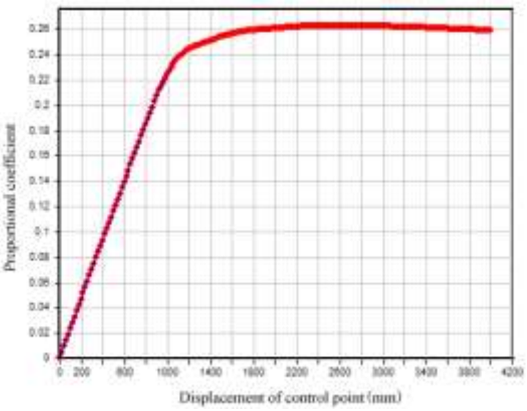


Fig. 6 The curve of load-displacement of control point

The analysis results of elastic-plastic stability for the Yangtze River Bridge show that the L/4 position of the bottom chord section close to the left bank begin to enter the plastic working state with the increase of the load,and then the plastic region continues to expand,subsequently the upper chord section of the left arch foot,the L/4 position upper chord section close to the right bank enter the plastic working state in succession,finally the bottom chord section of the arch foot close to the right bank enter plastic working state.Now the structure become unstable and reach its ultimate bearing capacity.

III. CONCLUSION

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

（1）The result of analysis on linear elastic stability of the Yangtze River Highway Brige show that the safety coefficient is 92.7.When the nonlinear effect is took into consideration, the safety coefficient of it is 14.0.It illustrate that the stability and ultimate bearing capacity satisfied the requirement of design and standard.

（2）Under the influence of nonlinear effect, the safety coefficient of structure is much smaller than the safety coefficient of linear elastic instability.While we can see that geometric and material nonlinearity can’t be ignored in the calculation of ultimate bearing capacity of large-span steel box truss arch bridge.

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