STUDY AND EXPERIMENTS ON THE LONG-SPAN STEEL-BOX STACKED ARCH BRIDGE OF HIGH-SPEED RAILWAY

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SUMMARY

It is a new arch system for stacked arch bridge, in which parts of the arch ribs are separated into upper and lower arch ribs in a plane and their skewbacks are fixed on a same pier or different piers. Taken Xinkai River steel-box stacked arch bridge of Harbin-Dalian high-speed railway as a study case, the space finite element model is established in this paper. Then the static performance of Xinkai River Bridge under operation state is calculated to analyze the stresses and deformations. Also, the actual monitoring values and the numerical values of the suspender stresses under construction stage are compared and studied.

Keywords: *Bridge engineering, high-speed railway, steel-box stacked arch bridge, calculation analysis, suspender stress.*

1. INTRODUCTION

Stacked arch bridge is a new arch system, in which parts of the arch ribs are separated into upper and lower arch ribs in a plane and their skewbacks are fixed on a same pier or different piers. Xinkai River Bridge is located in Changchun, Jilin Province, which is a key project of the Harbin-Dalian high-speed railway. The structure form of this bridge is steel-box stacked arch bridge, and the three-dimensional effect diagram is shown in Fig. 1.

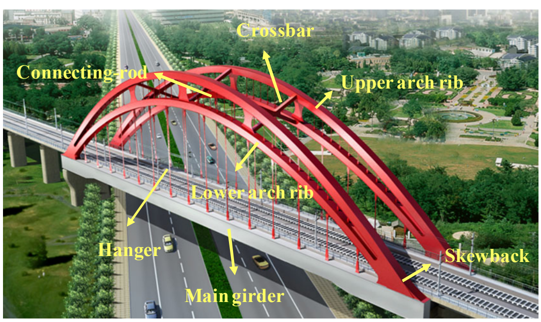

Fig. 1. 3D effect diagram of Xinkai River Bridge.

In this bridge system, arch ribs are separated into upper and lower arch ribs and the section forms of them is steel box girder. Upper and lower arch ribs in the same plane are connected by connecting rods, and arch ribs in two parallel planes are connected by X-shaped crossbars. The span of Xinkai River Bridge is 138m, which is classified as a large-span arch bridge in the railway bridges, so stability characteristics of this bridge is very important in design. Taken Xinkai River Bridge as a study case, effects of quantity, location, rigidity and form of crossbars on stability coefficients are discussed in this paper. Considering the impact of the pier size and the layout of roads, Xinkai River Bridge adopts steel-box stacked arch bridge design scheme with the span of 138m, and the elevation is shown in Fig. 2.

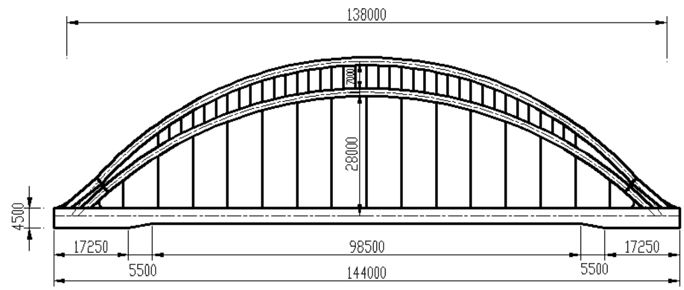

Fig. 2. *Elevation of Xinkai River Bridge (mm).*

Arch ribs adopt steel box girder of equal section with width of 2m, height 1.8m; upper and lower arch ribs are welded in skewbacks. The horizontal center space between two parallel arch ribs is 16m; center lines of upper and lower arch ribs are both quadratic parabolas; the vector height of upper arch rib is 35m and of lower arch rib is 28m. Arch ribs in two parallel planes are connected by three X-shaped crossbars, which adopt steel box girder of equal section; the longitudinal space between crossbars is 24m. Main girders adopt steel box girder of equal width and variable height. There are four I-Steel longitudinal beams of equal height which distributed under the bottom of tracks of each line. End cross beams adopt steel box girder of equal section and other cross beams adopt I-Steel beams of equal height; upper and lower arch ribs in the same plane are connected by Q460 solid steel rods; the diameter of connecting rods is 100mm and center space between them is 2.667m. Hangers adopt Q460 solid steel rods; the diameter of hangers is 130mm and center space between them is 87m.

2. TECHNICAL STANDARDS

Xinkai River Bridge adopts double-line high-speed railway, and the distance between centers of tracks is 5.0 m.

Design dead loads: structural weight.

Design live loads: ZK live load.

Design speed: 350 km/h.

Earthquake parameters: the peak acceleration value is 0.10 g (equivalent to seven degrees of basic earthquake intensity), and the characteristic period of the seismic response spectrum is 0.45s.

Track type: ballastless track.

3. ESTABLISHMENT OF FINITE ELEMENT MODEL

The space finite element model of Xinkai River Bridge is established and stability characteristics of this bridge are analysed by using the finite element analysis software Midas Civil. Longitudinal beams, cross beams, main girders, suspenders, crossbars and arch ribs are simulated as beam elements, and concrete deck is simulated as plate elements. The space finite element model is shown in Fig. 3.

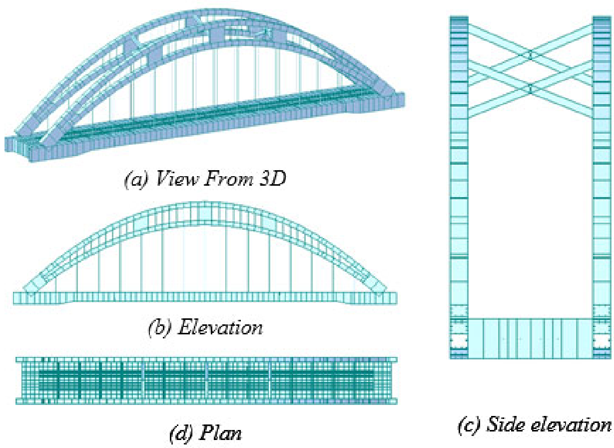

Fig. 3. *Finite element model of Xinkai River Bridge.*

3.1. Load combination

Table 1. *Load combination*

No.	Load combination	Loads
1	dead load	self-weight + secondary dead load
2	main load	self-weight + secondary dead load + double line ZK live load
3	main load + additional warming	self-weight + secondary dead load + double line ZK live load+ overall warming 28□
4	main load + additional cooling	self-weight + secondary dead load + double line ZK live load + whole bridge overall cooling 46.5□
5	main load + additional wind load	self-weight + secondary dead load + double line ZK live load + wind load

3.2. Stresses of main structures

The maximum stresses of main structures under each load combination are summarized in Tab. 2.

Table 2. *The maximum stresses of main structures (MPa).*

Number of load combination	Arch rib	Main girder	Longitudinal beam	Cross beam	Suspender
1	72.68	52.17	38.97	37.82	121.68
2	96.82	78.52	61.47	64.62	170.40
3	99.90	76.73	57.69	111.16	172.74
4	94.38	83.45	69.34	160.50	169.59
5	111.62	79.03	61.36	64.54	208.92

As shown in Tab. 2, under each load combination, the maximum stress of longitudinal beam is the maximum stress of main girder is 83.45 MPa, the maximum stress of longitudinal beam is 69.34 MPa, the maximum stress of cross beam is 160.50 MPa and the maximum stress of suspender is 208.92 MPa. All the maximum stresses of main structures meet the requirements of standards.

3.3. Structural deformations

Under each load combination, the maximum vertical deflection of main girder is 3.08 cm. As regulated in The Interim Design regulations of New 300-350 km/h Passenger Dedicated Railway, under ZK live load, the maximum vertical deflection of main girder could not be greater than L/1000=13.8 cm, the structural deformation satisfies specified requirements. The deformation shape of structure is shown in Fig. 4.

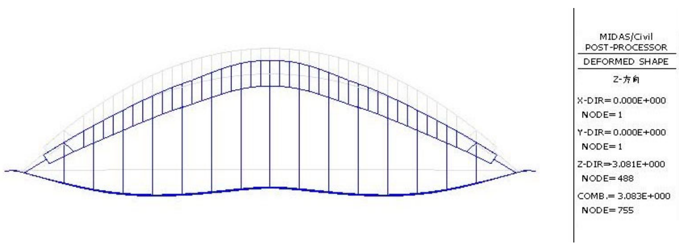

Fig. 4. *Vertical deflection of arch bridge.*

4. CONSTRUCTION MONITORING OF SUSPENDER STRESSES

Relative to the external structure, the tied-arch bridge is determinate structure, but its internal structure is high-order statically indeterminate structure. Any change of the internal force of each suspender will have influence on the stress state of the whole bridge, especially on the internal forces of the adjacent suspenders. According to the above reason, internal forces and the line shape of structure could meet the design requirements by adjusting internal forces of suspenders.

In design stage, there are a lot of schemes in deciding internal forces of suspenders under dead loads for construction stage. The reasonable determination of internal forces of suspenders could bring smooth line shape, reasonable stress state and lower requirement for foundation. By calculating stretching control forces of suspenders and monitoring changes suspender stresses, forces of suspenders could meet the design value, which can shorten construction time and save construction cost.

The geographical position of Xinkai River Bridge is vulnerable to seasonal climate change and big thickness of snow, so the stability and security of the structure are particularly important in construction stage. In order to ensure that structure stress and deformation is always in a safe range in the construction stage, the line shape finished bridge meets the design requirements and internal forces of structure under dead load are close to the design expectations, Strict construction control must be carried out in construction process. Considering that Xinkai River Bridge cross the road, construction method for Xinkai River Bridge adopts “beam first, then arch”, which needs setting up temporary piers and temporary supports. Temporary piers are using for bearing loads of bridge deck system, and temporary supports are set up between main girders and arch ribs to bear loads of arch ribs and prevent displacement of arch ribs. Temporary supports will be dismantled after the completion of the arch ribs, and then bridge deck system will be constructed. Finally suspenders will be installed in the design sequence. Strain slices are pasted on lower side of each suspender to test all the internal forces of suspenders. After installation of suspenders, tensioning of suspenders should be carried out to ensure that each suspender is in tensional state. The calculated value and the measured value of suspender stresses are compared as follows.

4.1. After the demolition of suspenders

Table 3. *The calculated value and the measured value of suspender stresses after the demolition of suspenders (MPa).*

No.	Suspenders of north side calculated value	measured value	error	No.	Suspenders of south side calculated value	measured value	error
N1	49.83	43.85	-12.01	S1	49.83	52.18	4.72
N2	70.92	67.26	-5.15	S2	70.92	73.25	3.28
N3	75.88	74.07	-2.39	S3	75.88	87.79	15.69
N4	75.64	83.03	9.77	S4	75.64	88.56	17.08
N5	76.43	70.52	-7.73	S5	76.43	83.38	9.09
N6	75.63	71.60	-5.33	S6	75.63	72.42	-4.24
N7	75.23	62.99	-16.27	S7	75.23	83.62	11.16
N8	75.91	74.86	-1.38	S8	75.91	86.95	14.55
N9	75.23	79.01	5.03	S9	75.23	77.88	3.53
N10	75.63	81.17	7.32	S10	75.63	71.09	-6.00
N11	76.43	74.15	-2.99	S11	76.43	71.67	-6.22
N12	75.64	74.75	-1.17	S12	75.64	89.13	17.83
N13	75.88	82.82	9.15	S13	75.88	70.46	-7.14
N14	70.91	67.97	-4.15	S14	70.91	67.35	-5.02
N15	49.83	63.49	27.42	S15	49.83	59.00	18.40

4.2. After pouring bridge deck concrete

Table 4. *The calculated value and the measured value of suspender stresses after pouring bridge deck concrete (MPa).*

Suspenders of north side				Suspenders of south side			
No.	**calculated value**	**measured value**	**error**	**No.**	**calculated value**	**measured value**	**error**
N1	61.12	58.16	-4.84	S1	61.12	59.05	-3.39
N2	96.77	102.89	6.33	S2	96.77	104.21	7.69
N3	105.56	104.48	-1.02	S3	105.56	107.66	1.99
N4	104.95	109.99	4.80	S4	104.95	109.90	4.72
N5	103.77	99.87	-3.76	S5	103.77	100.46	-3.19
N6	103.29	99.05	-4.10	S6	103.29	99.52	-3.65
N7	103.14	105.96	2.73	S7	103.14	108.24	4.95
N8	103.13	101.71	-1.38	S8	103.13	99.30	-3.71
N9	103.14	108.25	4.96	S9	103.14	108.42	5.12
N10	103.29	101.52	-1.72	S10	103.29	99.02	-4.14
N11	103.77	99.91	-3.72	S11	103.77	98.51	-5.07
N12	104.95	106.95	1.91	S12	104.95	107.64	2.56
N13	105.56	109.31	3.55	S13	105.56	108.47	2.76
N14	96.77	93.39	-3.49	S14	96.77	94.82	-2.02
N15	61.12	59.29	-2.99	S15	61.12	62.15	1.69

After the demolition of suspenders, the measured values of stresses of suspenders of north side are smaller but basically correspond to he calculated ones. Tensioning of suspenders has obvious influence on the internal forces of the adjacent suspenders.

5. VIBRATION CHARACTERISTIC ANALYSIS OF ARCH BRIDGE

Subspace iteration method is used to analyse the vibration characteristic of arch bridge. It meet the condition that the accumulation of longitudinal, transverse and vertical participate in quality are more than 90%. Due to the different mass distribution, it divided into cars on the bridge and no car on the bridge two cases. The first ten order modal analysis results such as table 5 to table 6.

Table 5. *Table of self-vibration characteristic of no vehicle on Bridge.*

Vibration mode	Frequency [Hz]	Cycle [sec]	Modal characteristics
1	0.5894	1.6965	Arch rib side
2	1.3306	0.7516	Arch, bridge deck is antisymmetric vertical bending + The left side pier
3	1.5257	0.6554	Arch, bridge deck is antisymmetric vertical bending
4	1.5283	0.6543	Arch, bridge deck symmetric transverse bending
5	1.6122	0.6203	Arch bridge deck symmetric transverse bending
6	2.2257	0.4493	Symmetrical vertical bending of arch and bridge deck
7	2.9950	0.3339	Symmetrical vertical curve of second order of arch and bridge deck
8	3.1880	0.3137	Second order symmetric horizontal bend of arch
9	3.2387	0.3088	symmetric horizontal bend of arch and bridge deck
10	3.4004	0.2941	Bridge Deck System Second Order twist

Table 6. *Table of self - vibration characteristic with vehicle on Bridge.*

Vibration mode	Frequency [Hz]	Cycle [sec]	Modal characteristics
1	0.5892	1.6973	Arch rib side
2	1.3306	0.7515	Arch, bridge deck is antisymmetric vertical bending + The left side pier
3	1.4689	0.6808	Arch, bridge deck is antisymmetric vertical bending
4	1.5257	0.6554	Arch, bridge deck symmetric transverse bending
5	1.6119	0.6204	Arch bridge deck symmetric transverse bending
6	2.2259	0.4493	Symmetrical vertical bending of arch and bridge deck
7	2.9952	0.3339	Symmetrical vertical curve of second order of arch and bridge deck
8	3.1682	0.3156	Second order symmetric horizontal bend of arch
9	3.1855	0.3139	symmetric horizontal bend of arch and bridge deck
10	3.3966	0.2944	Bridge Deck System Second Order twist

Due to the vibration characteristic analysis of arch bridge, we can draw the following conclusions:

1) The fundamental frequency of Xinkai River bridge is 0.59 Hz. The overall stiffness of Xinkai River bridge is small. The first order modal of Xinkai River bridge is lateral overturning of arch rib. Its frequency is much larger than the second order frequency. The lateral stiffness of arch rib is small. Bridge's lateral rigidity is far less than the longitudinal stiffness and vertical stiffness. Transverse vibration of arch rib is easy to occur in earthquake.
2) The second、fourth、sixth、seventh order modal of Xinkai River bridge is along the vibration rib and bridge deck. Because of the boom connected between arch and deck system, which make ache、boom、bridge deck composition of vertical common force system, the vertical vibration of each order is shown as the synchronous vibration of the arch rib and the bridge deck system..
3) The third、fifth、eighth、ninth order modal of Xinkai River bridge is transverse vibration of rib. The third、eighth order modal accompanied by transverse vibration of bridge deck system. There are two lateral support linked between the arch rib,so the two arch ribs showed synchronous lateral vibration.
4) Because of the boom between the arch and the bridge deck system, which horizontal frame structure is formed between the end of the beam and the tie beam, make the torsional stiffness of the bridge larger. Therefore, torsional vibration appears in the tenth order mode.
5) The research shows that the frequency range of the human body is sensitive to the vibration is 2~6Hz. First five natural frequencies of The Xinkai River bridge were less than 2Hz. Therefore, the vibration will not cause human's discomfort. In addition, the speed of the high-speed train through the bridge is less than 300km/h, which generated vibration frequency is about 5Hz.The frequency is larger than the first ten self vibration frequency. Therefore, the resonance of the bridge will not be caused by the train passing through.

Reference the provisions of the 《General specifications for design of highway bridges and culverts》(JTGD60-2004)[132], arch bridge base frequency according to the following formula to calculate:

$$f_1 = \frac{\omega}{2\pi l^2} \cdot \sqrt{\frac{EI_c}{m_c}} \tag{1}$$

$$\omega = 105 \times \frac{5.4 + 50f^2}{16.45 + 334f^2 + 1867f^4} \tag{2}$$

f_1 - Base frequency (Hz)；

l - Structural calculations Span (m)；

ω - Frequency coefficients；

f - Span ratio of arch bridge；

E - Elastic modulus (N/m2) ;

I_c - Sectional moment of inertia in the the middle section (m4) ;

m_c - Mass per unit length at the mid-span structure (kg/m)。

Calculation result $f_1 = 0.7317\text{Hz}$ 。

References literature [133] research content, tied arch base frequency in accordance with the formula 3 and 4:

$$I_{eq} = I_0 + \frac{6}{\pi^2}\frac{S_0^{\ 2}}{Bd}n_H I_H + \frac{8}{\pi^2}\frac{S_0}{L_0}\cos^2\theta_0 n_L I \tag{3}$$

$$f = \omega / 2\pi = \frac{\pi}{2S_0^{\ 2}} \cdot \sqrt{\frac{E_0 I_{eq}}{m}} \tag{4}$$

I_0 - Ribs transverse moment of inertia (m4) ;

S_0 - Arch axis arc length (m) ;

B - Center distance of arch rib (m) ;

d - Spacing of transverse bracing (m) ;

L_0 - Span of arch bridge (m) ;

θ_0 - Angle of arch and tie beam ;

n_H - Elastic modulus ratio of crossbars and ribs, $n_H = E_H / E_0$;

n_L - Elastic modulus ratio of tie beam and arch rib, $n_L = E_H / E_L$;

E_0 - Elastic modulus of rib (Pa) ;

E_H - Elastic modulus of crossbars (Pa) ;

E_L - Elastic modulus of tie beam (Pa) ;

I_H - Inertia distance of crossbars (m4) ;

I - Inertia distance of tie beam (m4) ;

m - Average line quality of singal rib (kg/m) ;

f - frequency (Hz) ;

I_{eq} - Equivalent moment of inertia (m4) ;

ω - Angular frequency (rad/s)。

Calculation result $f_1 = 0.6023\text{Hz}$ 。

Comparison of finite element calculation、the simplified formula of highway bridge design code and three result of fundamental tied arch formula, we can find that he bridge frequency is about 0.6Hz. The overall stiffness is small. The first order vibration mode of the bridge is the lateral overturning of the arch rib, the lateral stiffness of arch rib is small. Bridge lateral rigidity is far less than the longitudinal stiffness and vertical stiffness ; The second、fourth、sixth/seventh order modal is along the vibration rib and bridge deck, Because of the boom connected between arch and deck system ,which make ache、boom、bridge deck composition of vertical common force system, the vertical vibration of each order is shown as the synchronous vibration of the arch rib and the bridge deck system; The third、fifth、eighth、ninth order modal is transverse vibration of rib. The third、eighth order modal accompanied by transverse vibration of bridge deck system. There are two Lateral support linked between the arch rib, so the two arch ribs showed synchronous lateral vibration ; Because of the boom between the arch and the bridge deck system, which horizontal frame structure is formed between the end of the beam and the tie beam, make the torsional stiffness of the bridge large. Therefore, torsional vibration appears in the tenth order mode.

Stability analysis of steel box composite arch bridge

The stability analysis of the spatial curved rod system is included first class stability analysis based on bifurcation point stability theory and the second kinds of stability analysis based on the theory of extreme point instability. In engineering applications. The simplify solution of linear stability method to analysis first class stability problem. The essence stable buckling analysis for linear problems is to solve the eigenvalue of 3-5 equation

$$\left| K + \lambda K_G \right| = 0 \tag{5}$$

K - Elastic stiffness matrix of the structure ;

K_G - integration stiffness matrix of the structure ;

λ - Stable characteristic value。

In considering dead load and ZK load, first order buckling mode of Xinkai River bridge is antisymmetric, buckling outside surface, as shown in Fig. 3. For the first order buckling coefficient is 14.42. Bridge's structure is safe.

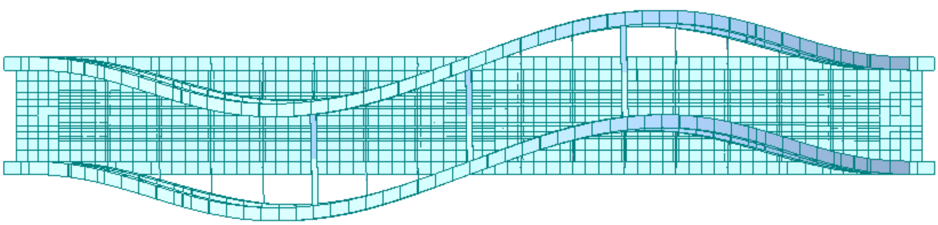

Fig. 5. *The first order buckling mode of Xinkai River Bridge.*

6. CONCLUSION

As a new type arch bridge structure, steel-box stacked arch bridge is used in engineering application for the first time in China. Because this kind of bridge is very novel, the construction monitoring is directly related to the construction quality, economic benefit and even the success of construction. Especially Xinkai River Bridge adopts rigid suspenders, tensioning of suspenders is very important for the linear control of the whole bridge

In the construction process, the demolition of suspenders and pouring bridge deck concrete would bring sharp changes of internal forces of structure, and also stresses and deformation of structure are greatly influenced. Besides, construction load, environmental temperature and humidity, sunshine duration and other factors would possibly make arch bridge construction develop in a deviating direction from the intended target. Suspenders in high stress level bar would endanger the safety of the whole structure. In conclusion, construction monitoring is indispensable for the long-span steel-box stacked arch bridge.

ACKNOWLEDGMENT

The authors wish to thanks below: This research work has been supported and provided financial aid by science and technology development program of Ministry of Railways, contract number: 2008G007-E. At the same time, it has been supported and provided financial aid by National Natural Science Foundation of China, contract number: 50878020 and 51178042. China Railway Corporation Science and technology research and development program (2014G004-B); China Communications Construction Co technology research and development project (2014-ZJKJ-03).

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