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RESEARCH ON INTELLIGENT SYNCHRONOUS TENSION MONITORING OF SUSPENDER OF THROUGH ARCH BRIDGE

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ABSTRACT

Suspender tension and cable adjustment are important construction procedures in the construction of through arch bridges. The traditional suspender tension method is asynchronous tension. Because it is tensioned in batches and manually reads, it will cause errors in the control of suspender tension, which often fails to reach the tension accuracy. Therefore, it is necessary to determine whether secondary cable force adjustment is needed according to the site conditions, which may increase the construction period, management cost and construction cost. In this paper, the overall intelligent synchronous tensioning technology is applied to a through arch bridge. By monitoring the measured suspender cable force, structural deformation and structural stress in the synchronous tensioning process and comparing them with the theoretical values, the traditional asynchronous tensioning technology and intelligent synchronous tensioning technology are compared based on the finite element software. The influence of the error caused by asynchronous tensioning on the structure is analyzed and compared with the suspender cable force, structural stress and structural deformation in the synchronous tensioning process. The results show that the bridge is relatively sensitive to the tension cable force, so it is necessary to accurately control the construction cable force. The overall intelligent synchronous tensioning technology can control the error of the suspender cable force within 3% during the bridge completion process, the geometric shape error of the whole bridge is controlled within 4mm, and the stress error is within 7MPa, avoiding the secondary cable force adjustment. It not only reduces the structural stress generated during the construction of the suspender, but also saves the construction period and construction cost, and ensures the safety of the construction process.

KEYWORDS

Through arch bridge, Synchronous tensioning, Suspender, Cable adjustment

INTRODUCTION

The through arch bridge is a combination of beam and arch bridge with light structure, beautiful line shape and strong spanning ability. It combines the advantages of both and has low cost [1]. It is widely used in the construction of urban and highway bridges in China. But its structure itself is a multiple statically indeterminate structure system [2-3]; arch rib and suspender are the main load-bearing components of through arch bridge, and the size of suspender cable force will directly affect the geometric shape and internal force distribution of the bridge and then affect the overall working state of the whole bridge [4]. Therefore, the installation and tension of the suspender is an important part of the whole construction. Improper tension control of the suspender will not only cause excessive stress to the main beam and arch rib, but also affect the geometric shape of the whole bridge, affect the normal operation of the bridge, and bring safety hazards to the construction [5], and the tension sequence will also have a greater impact on the geometric shape and stress state of the bridge [6].

The traditional suspender tension adopts the method of asynchronous tension, that is, the suspender tension and tension sequence are determined before the suspender tension, and the oil pressure jack is used to tension the suspender in batches according to the order set in advance and read the data. The construction monitoring party uses the vibration method [7-8] to measure the suspender cable force after tension. In the construction process, the post-tensioned suspender will play a role in loading or unloading the pre-tensioned suspender, which may cause the loss of over-tension or tension cable force [9]. Therefore, according to the actual situation of the construction site, it is decided whether secondary cable force adjustment is needed [10]. And in the construction process, it is impossible to control the cable force as a whole. In the adjustment of the cable force, it is necessary to repeatedly try different cable force combinations to achieve the design of the bridge cable force. The efficiency is low and the adjustment accuracy is not high [11]. Therefore, a new suspender tensioning method, namely the overall intelligent synchronous tensioning technology, is proposed.

The overall intelligent synchronous tensioning technology [12] was invented in 2015.Its working principle is based on the tension as the control index and the suspender elongation as the auxiliary control parameter. When the bridge is working, the control center sends out tensioning instructions to control the operation of each jack, and ' synchronously ' tensioning all the suspenders of the bridge. At the same time, it can also control the operation of a single or local jack, and perform ' asynchronous ' tension and boom force adjustment on the local suspenders of the bridge.

The overall synchronous tensioning system of suspender is mainly composed of control cabinet, intelligent jack, signal acquisition and transmission system and hydraulic oil circuit system. Intelligent equipment system control tension instead of manual construction operation, can improve the construction conditions, improve the construction accuracy, quality and reliability.

Connect the control center to multiple intelligent pump stations, with each intelligent pump station capable of connecting to 10 jacks. Each jack is connected to the pump station via separate oil inlet and return lines. At the pump station, each jack's oil inlet and return ports are equipped with a frequency converter and solenoid valve. The pump station's PLC adjusts the oil inlet and return rates of each jack based on the displacement and tension signals transmitted by the data acquisition box of each jack, in conjunction with instructions from the computer control center. By controlling the switch frequency of the solenoid valve, different tension rates for each jack are achieved.

All suspenders of the whole bridge are tensioned synchronously to avoid the influence of adjacency between suspenders. There is no need for iterative calculation and cyclic tension, which can shorten the construction period, avoid the installation and disassembly of jacks back and forth, and avoid safety risks. And all the suspenders of the whole bridge are slowly stretched in place, which is more in line with the design and calculation process of the bridge, and ensures that the construction quality of the bridge accurately meets the design indicators.

The tension process is automatically completed by the program. The tension force is used as the control index, the suspender elongation is used as the auxiliary control parameter. The loading pause point and the holding load are accurately controlled, and the force value and displacement are visualized without manual operation of the oil pump. The intelligent tension of the suspender and the adjustment of the boom force are displayed in real time during tension. The tension value can also be checked by the pressure value of the hydraulic oil meter, and the cable force monitoring can be realized at the same time of tension. The control accuracy of the force value reaches ±1%. The construction and monitoring are synchronized to reduce the alternating approach time and further shorten the construction period.

Engineering situation

In a certain bridge alignment, the angle between the normal to the centerline of the route and the centerline of the navigational channel is approximately 27.5°. The river channel at the crossing point is straight, with a water surface width of about 150m along the axis direction of the route. The main bridge is a double-layer simply supported steel truss steel arch bridge with a span of 150m and a total length of 153m. The main beam adopts fully welded double-layer trusses, with the main truss varying in height from 10.394 to 11.0792m and a main truss spacing of 37.3m. The arch ribs are set with a secondary parabolic curve, with a rise of 37.5m (measured from the centerline of the lower span system). Both the upper and lower bridge decks have a 2% cross slope in both directions.

The entire bridge has a total of 44 suspenders, with 22 each set on the north and south sides, designed as double suspenders. The spacing of the suspenders in the longitudinal direction of the bridge is 10.6m, and in the transverse direction, it is 1.2m. Each suspender is made of high-strength parallel steel wires with a diameter of 91*Φ7, with a tensile strength not less than 1670MPa.

Fig. 1 – Bridge real picture

Measuring point arrangement

1. Geometric shape monitoring points

Set up two monitoring sections at the front and rear ends of the main girder and set coordinate observation points at the top center positions of the monitoring sections on the top and bottom chord of bridge girders. The main arch observation point is located at the lifting lug installation, as shown in Figure 2. The geometric shape monitoring uses a high precision leveling instrument to measure the elevation of the monitoring point after each construction stage. The high precision leveling instrument has an error within 2mm/km, ensuring high accuracy of the measurement data.

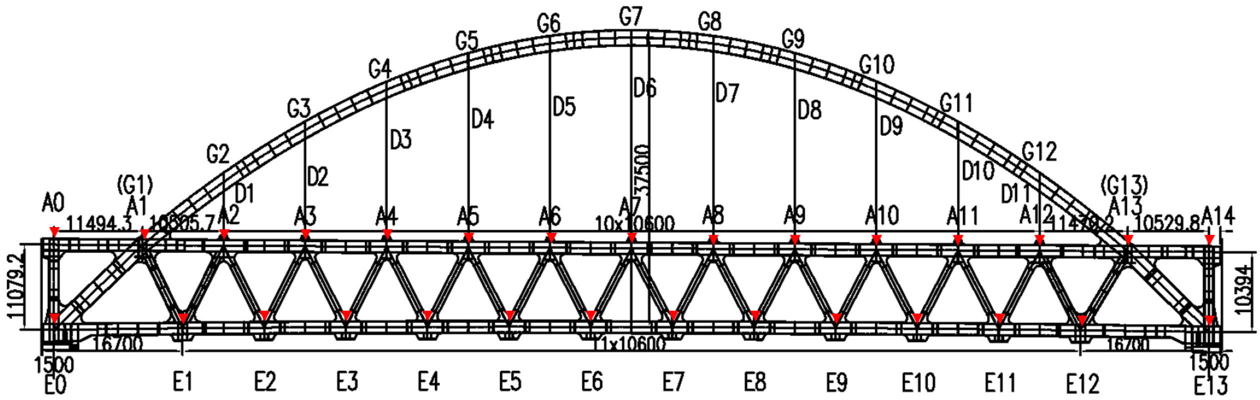

Fig. 2 – Bridge geometry monitoring points (mm)

2. Strain monitoring points

In order to better ensure the accuracy of the stress test results of the structure, on the basis of a large number of research on the commonly used strain sensors, the vibrating wire strain sensor is selected for monitoring. The error of the vibrating wire strain gauge sensor is within ±1.5% of the full scale.

The quarter cross section and the mid-span section of the steel truss girder are selected as the strain monitoring sections. Four strain monitoring points are set in the mid-span, and two strain monitoring points are set in the quarter cross section. The main truss has a total of 32 vibrating wire surface strain gauges. The layout of the monitoring section sensors is shown in Figure 3.

According to the results of structural analysis, and taking into account the symmetry of the two transverse arch ribs and the comparability of the data, the key sections of the bridge are arch foot section, quarter cross section and vault section. The monitoring section and the layout of the section sensor are shown in Figure 4, a total of 28 vibrating wire surface strain gauges.

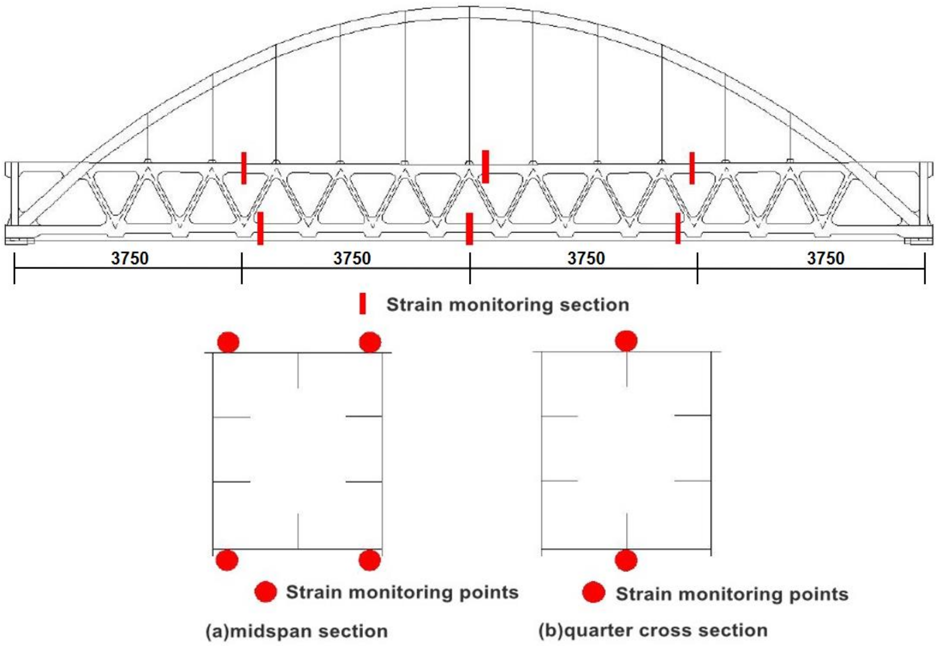

Fig. 3 – Strain monitoring point of main truss (unit : cm)

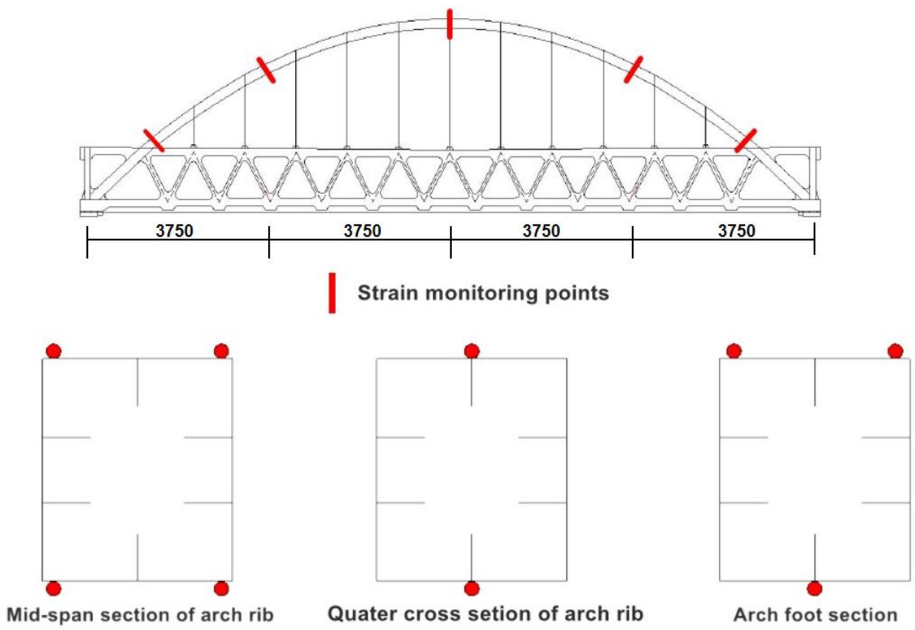

Fig. 4 – Arch rib strain monitoring point (unit : cm)

3. Cable force monitoring of suspender

In the construction control, based on the supervision of the measurement results of the jack of the construction unit, the environmental random vibration method (spectrum analysis method) is used to monitor the cable force. This method utilizes highly sensitive sensors temporarily attached to the suspenders to pick up the pulsating signals of the cables under environmental excitation.

In the process of suspender tensioning, the reading of the intelligent jack is used as the actual tensioning tonnage, and the vibration frequency method is used to monitor the cable force of each suspender during the tensioning construction process.

Fig. 5 – Application of integral intelligent synchronous tensioning technology in this bridge

Fig. 6 – Cable force measurement

4. Tension of suspender

During the construction process, due to the subsequent need to remove the lower support and other construction processes, the initial tension cable force of the boom is designed to be the bridge cable force through the forward iteration [13]. All suspenders of the entire bridge are tensioned in stages as a whole, with tensioning carried out in five steps, that is, pre-tension (total cable force 10%) → pre-tension unloading force → 30% (The first level tension) → 65% (The second level tension) → 100% (The third level tension). After the tension is completed, according to the cable force value displayed by the overall intelligent synchronous tension system and the cable force value measured by the construction monitoring, if the individual cable force does not meet the specification, the local single suspender cable force adjustment is carried out to make the final cable force meet the design and specification requirements.

Build finite element model

The spatial finite element model of the bridge is established by MIDAS Civil finite element software, as shown in Figure 7. Among them, the arch rib, main truss and main beam are simulated by beam element, and the suspender is simulated by truss element. The whole bridge is divided into 1617 nodes and 2896 elements, including 2874 beam elements and 22 truss elements. The diaphragm of the main bridge is simulated by a custom material without bulk density but with elastic modulus, and its weight is supplemented by the uniform load of the unit to simulate its role in the transverse connection of the bridge. Strictly follow the construction process set by the construction site to divide the construction stage of the model and fully consider the temporary load of each construction stage. There are four bearings at the end of the bridge, including one fixed bearing, two unidirectional movable bearings and one bidirectional movable bearing. The construction temporary support uses only compressive support to simulate the support effect of the support on the truss.

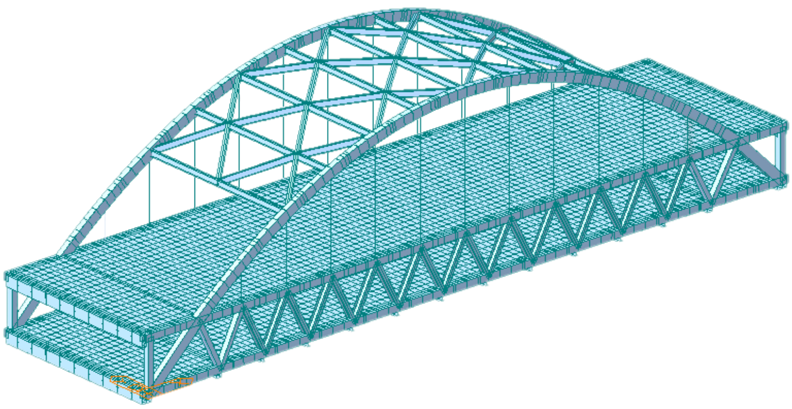

Fig. 7 – Bridge finite element model

Comparison of overall intelligent synchronous tensioning technology and asynchronous tensioning scheme

1. Comparison of initial cable force

In the original design scheme, the bridge adopted a symmetrical tensioning method from the crown to the arch feet at both ends as the suspender tensioning scheme, that is, D6 → D5 →... → D1 ; D6 → D7 →... → D11. However, in the end, due to the tight construction period of the project and the need for one-step tensioning in place, the overall intelligent synchronous tensioning technology is selected. The comparison between the initial tension cable force of the suspender and the overall intelligent synchronous tension cable force is shown in Figure 8.

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From the comparison, it can be seen that the cable force value of the asynchronous tension and the cable force distribution of the suspender present a ' W ' shape, which is evenly distributed on both sides of the synchronous tension cable force. The difference between the maximum cable force of the asynchronous tension and the maximum cable force of the synchronous tension is 253kN. The cable force of the bridge is basically symmetrical along the middle line of the bridge.

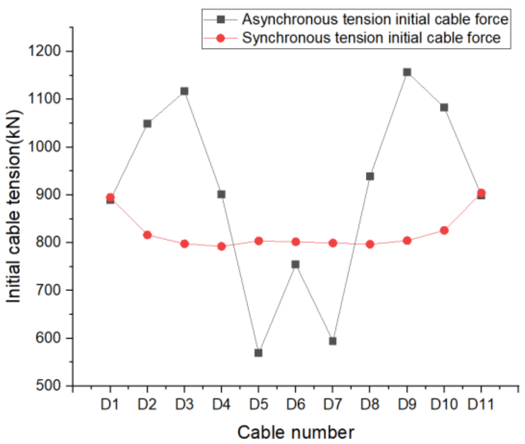

Fig. 8 – Comparison of initial cable force

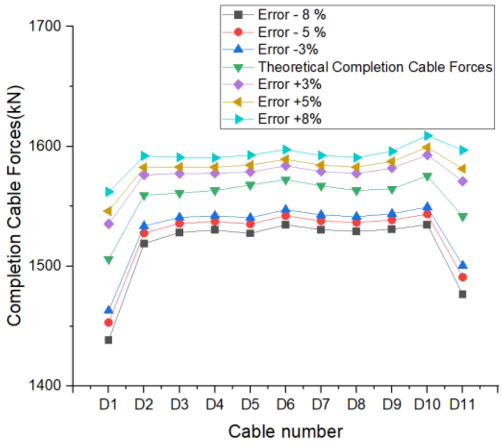

Fig. 9 – Comparison of Completion Cable Forces

If the asynchronous tensioning scheme is adopted, the difference between the maximum and minimum values of the initial tension cable force is 588kN, and after the synchronous tensioning scheme is adopted, the difference between the maximum and minimum values of the initial tension cable force is 111.5kN. Therefore, the difference between the maximum and minimum values of the initial tension cable force of the boom using the synchronous tensioning scheme is smaller than the difference between the maximum and minimum values of the initial tension cable force of the boom using the asynchronous tensioning scheme.

Therefore, it can be considered that the interaction between the suspenders of the bridge is more obvious, and the synchronous tensioning scheme can largely ignore the interaction between the suspenders, so that the initial tension cable force distribution is more average, the cable force distribution is relatively reasonable, and the local stress in the tensioning process is reduced, which is more conducive to the construction. However, the asynchronous tensioning scheme is adopted, and the difference of some cable force values is too large, which will lead to the excessive local stress in the tensioning construction process, which is relatively unfavourable to the construction process.

2. Comparison of Completion Cable Forces

Because the asynchronous tensioning adopts the method of manual batch tensioning, it is inevitable to produce the error of the tension cable force of the suspender. In this paper, the error values of the six asynchronous tensioning initial tension cable forces with error values of ±3%, ±5%, ±8% are used. The finite element software is used to calculate the Completion Cable Forces under the condition of error, and the synchronous tensioning Completion Cable Forces are compared, as shown in Figure 9.

Through the comparison in the figure, it can be seen that with the increase or decrease of the overall initial tension cable force error, the increase and decrease of the Completion Cable Forces of a single suspender are nonlinear. The reason for this situation is that the subsequent support removal and bridge deck pavement construction steps will cause the suspender cable force to be redistributed. However, on the whole, the distribution trend of Completion Cable Forces is basically the same. With the increase of error, the error of Completion Cable Forces also increases. When the maximum error of the initial tension cable force is ±8%, the maximum error of the Completion

Cable Forces will be-4.49% ~ +3.73%, but the cable force error is the error when all the suspenders increase by 8% or decrease by 8%. Since the initial tension cable force of the asynchronous tension is the cable force after the forward iteration optimization, the interaction between the suspenders has been considered in the iteration process, and the actual tension on site should be a random error. The error range of the actual Completion Cable Forces will be larger than the theoretical simulation value. Therefore, if the traditional asynchronous tension is actually used, the secondary cable force adjustment is required.

3. Geometric shape comparison

Because the stiffness of the main beam of the bridge is much larger than that of the arch rib, the displacement of each node of the main truss in the finite element model is basically the same during the simulation of tension, and the two sides of the bridge are symmetrical. Therefore, only the actual displacement of the unilateral arch rib node is compared, as shown in Fig.10.

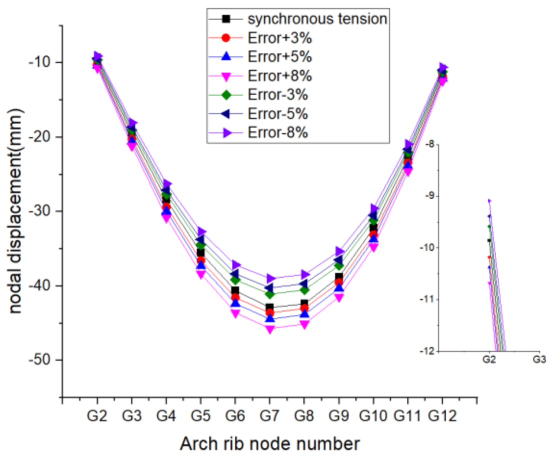

Fig. 10 – Arch rib node displacement comparison

Tab. 1 - Displacement error table of arch rib node caused by cable force error(unit:mm)

node number	Error +3%	Error +5%	Error +8%	Error -3%	Error -5%	Error -8%
G2	-0.3	-0.5	-0.8	0.3	0.5	0.8
G3	-0.7	-1.1	-1.7	0.5	0.9	1.5
G4	-1.0	-1.5	-2.4	0.8	1.3	2.2
G5	-1.0	-1.8	-2.8	1.1	1.8	2.8
G6	-0.9	-1.7	-3.0	1.5	2.3	3.5
G7	-0.7	-1.6	-2.8	1.8	2.7	3.9
G8	-0.6	-1.4	-2.7	1.9	2.7	4.0
G9	-0.8	-1.5	-2.7	1.5	2.3	3.4
G10	-0.9	-1.5	-2.5	0.8	1.3	2.5
G11	-0.7	-1.2	-1.9	0.6	1.1	1.8
G12	-0.4	-0.6	-1.0	0.3	0.5	0.9

As shown in the figure, as the error value increases, the overall arch rib node displacement will also increase, and vice versa. However, combined with the data in Table 1, it can be seen that taking the error of the suspender cable force as ±3% as an example, when the suspender cable force increases by 3% synchronously, the error value of the displacement at the arch foot is greater than the error value when the suspender cable force decreases by 3% synchronously. That is, the change of G2G3G4 node and symmetrical G10G11G12 node when the cable force increases by a fixed percentage is greater than that when the cable force decreases by a fixed percentage. In the middle of the arch rib span, the error of the suspender cable force is still ±3%. When the suspender cable force is reduced by 3% synchronously, the error value of the displacement in the middle of the arch rib span is greater than the error value when the suspender cable force is increased by 3% synchronously. That is, the change of G6G7G8 node when the cable force decreases by a fixed percentage is greater than that when the cable force increases by a fixed percentage. This trend can also be clearly seen in Figure 10.

4. Stress comparison

Because the construction steps of asynchronous tensioning are inconsistent with the construction steps of synchronous tensioning, the stress distribution of each section after tensioning is selected as a comparison. The stress changes of the upper and lower edges at the measurement points are basically the same. This paper analyzes the variation of stress on the upper edge, as shown in Figures 11 and 12.

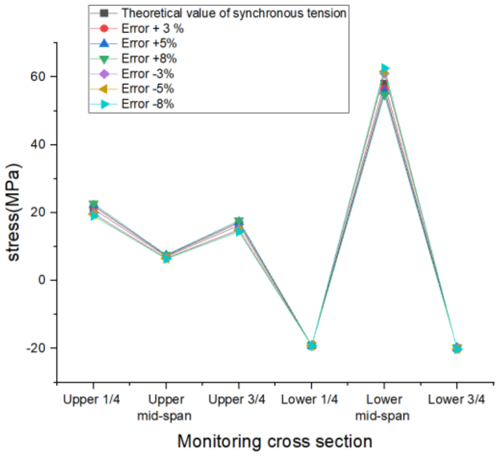

Fig. 11 – Main truss monitoring section stress comparison

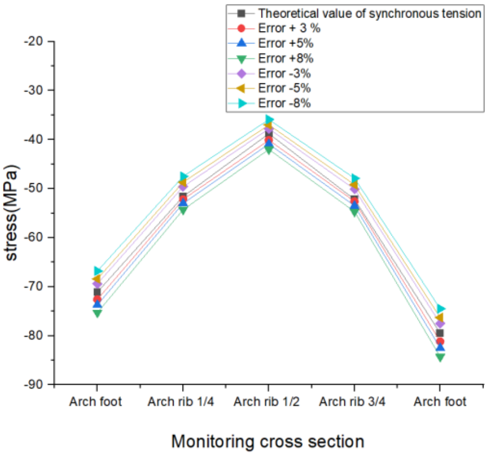

Fig. 12 – Arch rib monitoring section stress comparison

It can be seen from the comparison in the figure that with the increase of the suspender cable force error, the stress of the upper layer of the truss and the arch rib increases as a whole, and the stress of the lower layer decreases as a whole. This is because the increase of the cable force value of the suspender makes the arch rib and the upper truss share the load originally borne by the lower truss, which leads to the increase of the overall stress, which is consistent with the theoretical expectation. In the figure, the maximum stress error caused by the cable force is-5Mpa, and the position is the arch foot when the error is 8%. When the corresponding error is-8%, the stress error at the arch foot is 4.3Mpa, and the reason for the geometric shape trend of Section 3 is that when the overall suspender cable force error increases, the increase of the arch foot stress of the bridge is greater than the decrease of the overall suspender cable force error. When the overall suspender cable force error decreases, the change of the arch rib quarter cross section position and the mid-span position of the bridge is greater than the change at the arch foot position, which leads to the trend of the geometric shape of the bridge due to the cable force error.

Monitoring Numerical Analysis

1. Monitoring analysis of suspender cable force

Due to the symmetry of the arch ribs and main trusses on the left and right sides of the bridge, only the data of the cable force of the single-side suspenders and the suspenders after the completion of the bridge are listed, as shown in Table 2

From the comparison between the monitoring results of the suspender cable force and the theoretical calculation values, it can be seen that when the intelligent overall synchronous tension technology is applied to the bridge, the suspender tension cable force is distributed around 1560kN, and the suspender tension cable force is relatively average. The overall situation of the cable force of the suspender after multi-stage tension and completion of the bridge is close to the theoretical value; after the completion of the bridge, the deviation between all the suspender cable forces of the whole bridge and the theoretical bridge cable forces is within 3%, so it can be considered that the synchronous tension monitoring results meet the design requirements.

Tab. 2 - Suspender cable force monitoring value and theoretical value comparison

	The first level tension			The second level tension		
Suspender number	theoretical value (kN)	monitoring value (kN)	error%	theoretical value (kN)	monitoring value (kN)	error%
D1	268	294	9.7%	582	620	6.6%
D2	245	241	-1.6%	531	516	-2.8%
D3	239	221	-7.7%	519	496	-4.4%
D4	238	221	-7.0%	515	477	-7.4%
D5	241	236	-2.1%	523	526	0.6%
D6	241	231	-4.1%	521	514	-1.4%
D7	240	223	-7.1%	520	475	-8.6%
D8	239	230	-3.7%	518	493	-4.9%
D9	241	254	5.4%	523	548	4.8%
D10	248	245	-1.0%	537	556	3.5%
D11	271	275	1.4%	588	579	-1.5%
	The third level tension			Bridge completed		
Suspender number	theoretical value (kN)	monitoring value (kN)	error%	theoretical value (kN)	monitoring value (kN)	error%
D1	895	930	3.9%	1506	1540	2.3%
D2	816	791	-3.1%	1559	1537	-1.4%
D3	798	772	-3.3%	1561	1538	-1.5%
D4	792	777	-2.0%	1563	1551	-0.8%
D5	804	821	2.1%	1568	1588	1.3%
D6	802	817	1.9%	1572	1591	1.2%
D7	799	760	-4.9%	1567	1532	-2.3%
D8	797	752	-5.6%	1563	1522	-2.6%
D9	804	846	5.2%	1565	1609	2.9%
D10	826	856	3.6%	1575	1608	2.1%
D11	904	924	2.2%	1542	1564	1.5%

2. Geometric shape monitoring analysis

Because the bridge is constructed with full support, and the stiffness of the main truss of the bridge is much larger than that of the arch rib, it is a rigid beam flexible arch system. For the rigid beam flexible arch system, the tension of the suspender is mainly to adjust the internal force of the arch rib, and it does not have the function of adjusting the geometric shape of the main beam [14]. Therefore, the geometric shape of the main truss is compared with the displacement before and after the complete tension, as shown in Figures13 ~ 15.

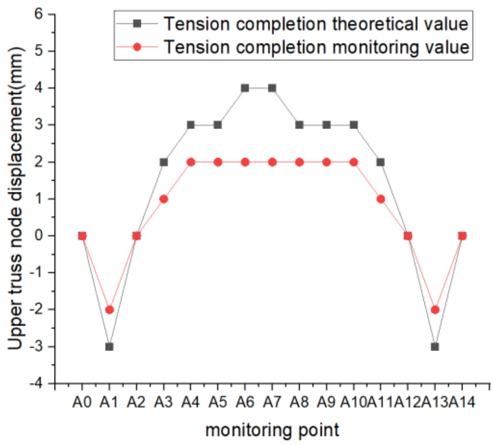

Fig. 13 – Displacement comparison of upper truss joints before and after tension

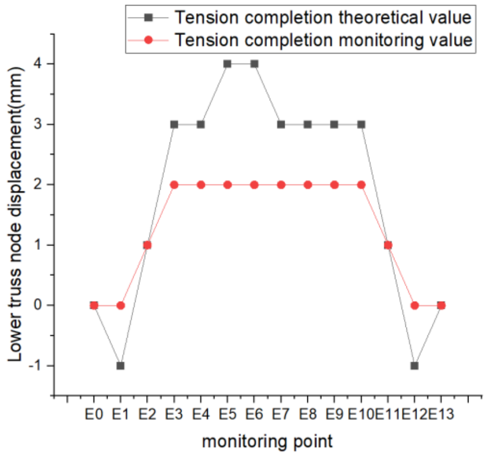

Fig. 14 – Displacement comparison of lower truss joints before and after tension

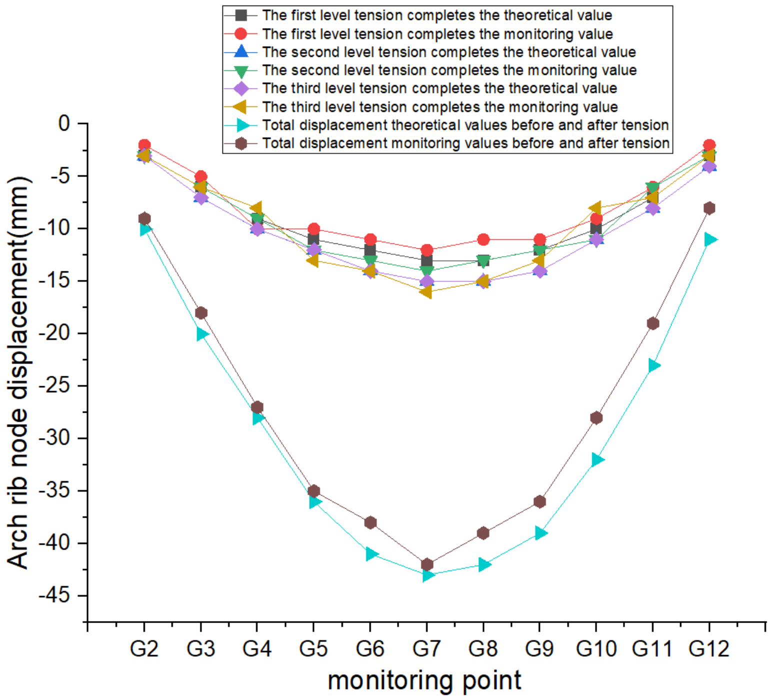

Fig. 15 – Arch rib displacement comparison

By comparing the displacement values of each node of the main truss and arch rib before and after tensioning, it can be seen that during the tensioning process, the maximum displacement of the upper and lower main girder trusses occurs in the middle of the span, and the maximum displacement after tensioning is 3mm. The displacement of the arch rib increases with the tension of the suspender. The maximum displacement occurs at the mid-span position after tension, and the maximum value is 43 mm. The displacement error of the whole bridge is controlled within 4 mm. From the comparison of the maximum displacement value of the arch rib and the main beam truss, it can be concluded that the overall stiffness of the main beam of the bridge is indeed much larger than the overall stiffness of the arch rib. In Figures 13 ~ 15, it can be seen that there is an obvious bulge in the displacement change of the theoretical value of the main girder truss at the A6A7 and E5E6 positions. This is because the bridge needs to meet the navigation requirements during the construction process, so there is no bracket at the navigation position of the river. In the theoretical model, in order to simulate the mid-span cantilever assembly, the boundary is not added in the mid-span. Therefore, in the tensioning stage, the cantilever assembly position will produce a large upward displacement relative to other positions of the main girder truss. During the monitoring process of the bridge, some measuring points have large deviations. The causes of the errors are personnel factors and environmental factors during the measurement, as well as the factors of the simulation accuracy of the full-bridge stiffness by the rod calculation model. However, on the whole, the overall change trend of the geometric shape monitoring value of the whole bridge is in good agreement with the theoretical calculation value.

3. Stress monitoring analysis

The bridge undergoes three-stage suspender synchronous tension during the construction process, and its stress state changes continuously with the construction. The stress monitoring data of the left truss and arch rib monitoring section of the bridge at each construction stage are listed below. Figures 16 and 17 are the comparison curves of the corrected stress data and theoretical analysis values of each monitoring section.

By comparing the stress monitoring values and theoretical calculation values of each section, it can be seen that the actual stress value and change trend of the whole bridge are in good agreement with the theoretical calculation values. The stiffness of the main girder of the bridge is large, so the stress change of the main girder section is relatively small during the tension process. The section with the largest change in stress is the mid-span position of the lower truss. The change value before and after tension is −27.44MPa, and the degree of stress change is close to the theoretical expected value of −31.27MPa. During the monitoring process, the difference between the monitoring value and the theoretical value of the 3/4 section at the arch rib is 7MPa, and the deviation is within the allowable range. The maximum stress is smaller than the material yield limit value specified in the specification, and the structure is in a safe state.

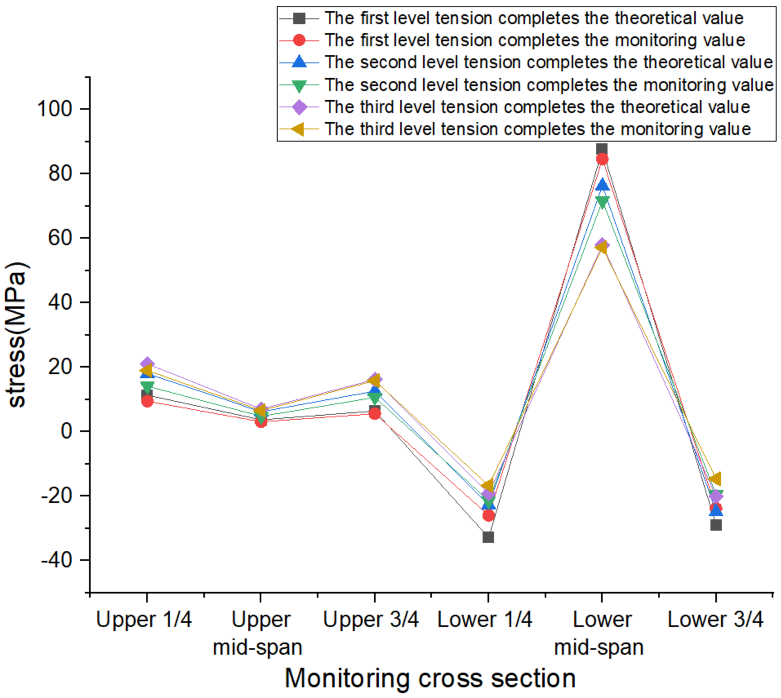

Fig. 16 – Main truss monitoring section stress comparison

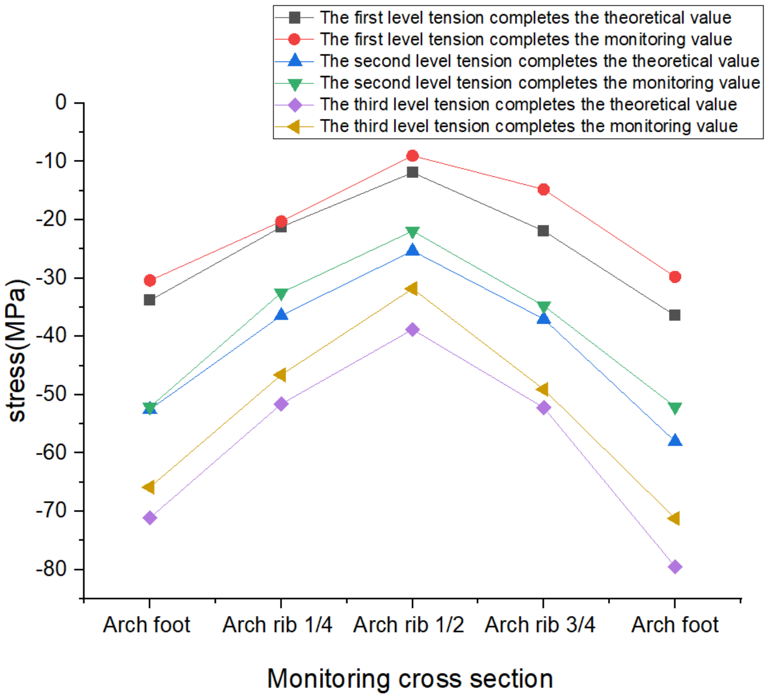

Fig. 17 – Arch rib monitoring section stress comparison

CONCLUSION

In this paper, based on the application of the overall intelligent synchronous tensioning in this project, and combined with the finite element software MIDAS Civil, the traditional tensioning method and the overall intelligent synchronous tensioning are compared and analyzed, and the conclusions are as follows.

(1) When the overall cable force of the suspender is greater than the design cable force, the increase of the force at the arch foot is greater than that at the mid-span of the arch rib, resulting in greater stress concentration at the arch foot. On the contrary, greater stress concentration will occur at the mid-span of the arch rib. Therefore, during the construction of the structural bridge, the cable force should be accurately controlled to prevent the construction safety problems caused by stress concentration.

(2) In the suspender tension construction process of the through arch bridge, the application of the overall intelligent synchronous tension technology can control the suspender cable force error within 3% during the bridge completion process. Compared with the traditional asynchronous tension method, the cable force control during the tension process is more accurate. It can control the local stress error of the bridge within 7MPa, prevent local large stress concentration and excessive local deformation during the tension process, and meet the design requirements.

(3) In the process of synchronous tensioning, because the whole bridge jack can be controlled at the same time, it is not necessary to move the jack with the traditional asynchronous tensioning, and the suspender can be tensioned in place at one time, which can avoid multiple iterative calculations, measurement and adjustment of cable force.

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