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Analysis and Research on Deformation Monitoring of Large Span Cable-stayed Bridge during Operating Period

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Abstract

This paper studies the alignment of bridge, the vertical displacement of the pier, the offset of the tower, the deformation of the expansion joints and cable force based on an extra large span cable-stayed bridge in Chongqing. Secondly, the contents and methods of large span cable-stayed bridge monitoring were introduced. Then, the theoretical value related to deformation of the bridge is calculated by using finite element software. After that, the bridge deformation data on the site was measured. Finally, the bridge alignment, tower vertical displacement, tower deformation, expansion joints, tower of the measured values and the theoretical calculation values were analyzed on the basis of comparison. It is concluded that the bridge is in normal working condition. The analysis and research of large span bridge in this paper provides the basis for similar Bridges, which has good practical value.

Keywords: bridge alignment, tower vertical displacement, tower deformation, expansion joints deformation, cable force, comparison analysis

1. Introduction

With the rapid development of China's economic, the bridge spans increase day by day. The cable-stayed bridge is one of popular styles of the long-span bridges. Compared with the suspension bridge, cable-stayed bridge is preferable in rigidity, economy, wind resistant stability, erection and so on (Zhou, 2004). However, factors, such as the heavy car traffic volume, destructive effects of overload and overweight vehicles, natural ageing of structures and materials cause large deformation of bridge structures. Thus, the deformation monitoring of bridge structure is more and more important.

The distress and accidents of cable-stayed bridge mainly occur on corrosions and wire broken, crack and deformation of girder and main tower. There are many related researches about deformation monitoring of long-span cable-stayed in China and abroad (Chen, Zhang, Zhou, Song, & Huang, 2013; Cho et al., 2010; Lekidis, Papadopoulos, Karakostas, & Sextos, 2013; Li, & Ou, 2006a, 2006b; Macdonald, 2003; Si, Au, & Li, 2013; Zengshun, Jun, Cheng, Guanrong, & Haoyang, 2013). Li Shunlong and other researchers assessed the conditions of stayed cable and damage monitoring of girder through the structural health monitoring system (Li et al., 2014). Cho, Soojin used wireless smart sensor technology to monitor the health of cable-stayed bridge under vibration load monitoring (Cho et al., 2010). However, the contents of the monitoring for large span cable-stayed bridge system are not comprehensive enough, especially in short-term deformation monitoring. Based on a long-span cable-stayed bridge, this paper analyzed the monitoring deformation value by finite element analysis software. And then, the calculated values and measured values were analyzed on the basis of comparison. The analysis of the long-span cable-stayed bridge deformation monitoring can provide a certain basis for similar bridge deformation monitoring and has good popularization value.

2. Engineering Situation

The large span cable-stayed bridge is located in the territory of the Shanghai-Chengdu Expressway in Chongqing. The total length of the Bridge is 992 m, of which the main bridge is 632 m. The main bridge is a pre-stressed concrete cable-stayed bridge with double pylons and double cable planes, total bridge span combination: 2 × (4 × 40 m (pre-stressed T beam) + (50 +108 +316 +108 +50) m (cable-stayed) +1 × 40 m (pre-stressed T beams) deck. Horizontal layout: 0.50 m (crash barrier) +10.75 (lane) +2.00 m (median strip) +10.75 (lane) +0.50 m (crash barrier).

The main Bridge girder used pre-stressed concrete structures separate trapezoidal cross-section with girder center height 3.00 m, roof thickness 0.25 m, width of the bottom of the triangular box 2.50 m, flanks thickness 0.25 m, vertical web thickness 0.35 m, box beam full width 27.40 m. The bridge was set two-way cross slope of 2%, formed by the box girder roof. The start block from the tower, No. 0 block length is 13.00 m and the standard block length is 6.00 m. The tower is of “H” shaped tower with hollow thin-walled box section. The tower along the bridge is 6.20 m and along width transverse direction is 4.00 m. the width of medial pylons is 4.00 m and the width of the under pylons grades by 5.85 m to 8.50 m and the width of the central pylons along the bridge to the top of the pylons to the bottom grades by 6.20 m to 10.00 m. The height of upper tower is 45.671 m and the medial tower is 43.379 m and the lowers tower is 25.15 m.

The top of auxiliary pier which under main girder and at the junction of the pier top was set with tension compression bearing. The top of the abutment and the 4th pier was set with a SSFB-80 expansion joint respectively; Each ends of the main bridge was set with a SSFB-320 expansion joint respectively.

Superstructure of the main bridge box girder used C60 concrete, tower and approach bridge with T beam by using C50 concrete. The main bridge pier, the junction pier, the auxiliary pier, the approach bridge pier and cap beam all with C40 concrete. All caps, juncture pier pile foundation, auxiliary pier pile foundation and abutment cap by using C30 concrete, the main bridge pier pile foundation by using C30 underwater concrete. Bridge elevation layout is shown in Figure 1.

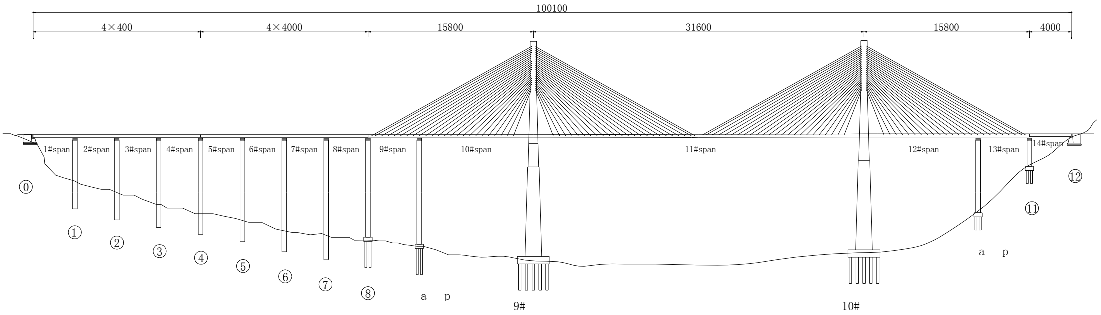

Figure 1. Bridge elevation layout (units: cm)

3. Deformation Monitoring Methods and Arrangement of Measuring Points

According to the usage of the bridge, the plane control network elevation control points, bridge alignment, tower deformation and expansion joints deformation of the bridge were monitored.

3.1 Deformation Monitoring Methods

3.1.1 Plane Control Network

Triangulation method is adopted to establish the plane control network, using LeicaTCR1201 total station (1 "level) with optical prism and the base, in accordance with the requirements for second grade leveling plane control network technology USES the traverse survey measured in the form of plane control network monitoring data.

3.1.2 Elevation Control Points

Elevation data were measured by NA2 Leica Precision Level (0.1 mm) with indium ruler. All level line observations in accordance with the requirements of national second-class leveling method form close level line. Station observation sequence, observation method, the results of overrun return measurements, weight measurements and so on are in accordance with the provisions.

3.1.3 The Bridge Alignment

Bridge deck alignment observation uses NA2 Leica Precision Level (0.1 mm) with indium ruler, according to the second-class leveling, the length of sighting line, sighting distance from start to finish and repeat counts of precision level measurements are conformed to the specification requirements of “Secondary Precision Level”. Inspect on I Angle of the Level before measurements, constitute the benchmark and bridge deck alignment observation points to a closed loop, measurements are in accordance with the observation sequence (1) odd station “back-front-front- back”, (2) even station “front- back- back - after”, the observation results are adjusted in addition.

3.1.4 Tower Deformation

Tower deformation monitoring usies Leica TCR1201 Total Station (1 "level) with optical prism. According to the requirements of secondary surface accuracy, the polar coordinate method is adopted to.

3.1.5 Expansion Joints Deformation

Expansion joints deformation monitoring includes both sides of the expansion joints (large pile side, small pile side) the deck transverse stagger displacement monitoring and transverse stagger displacement changes of itself (steel clearance) monitoring. Expansion joints on both sides of the bridge deck transverse stagger displacement monitoring uses total station with optical prism for measurement. And steel tape measurement is adopted to steel clearance changes of expansion joint itself directly.

3.1.6 Cable Force

(1) Test Methods

This test uses the frequency method to measure the cable force. When expressways completely closed, use precision vibration pick-up to pick up vibration signals under environment excitation or the attenuation of vibration signal after hitting. When testing, fixing the vibration pick-up on the cable so that the transverse vibration of the cable can be measured. Vibration pick-up transform random vibration signal into electrical signal, the electric signal was send to the dynamic signal acquisition system after enlargement and then was taken samples and stored. Through filtering, amplifying and spectrum analysis and the spectrum diagram again to determine the natural frequencies of the cable. Then calculate the cable force according to the measured natural vibration frequencies.

(2) The Cable Force Calculation Method

Regardless of the cable sag and the stiffness of the cable, and suppose the cable hinged at both ends, the cable force calculation formula as follow:

$$F = 4ml^2 \frac{f_n^2}{n^2} = K \frac{f_n^2}{n^2} \tag{1}$$

Where;

n is cable natural frequency modal order of natural vibration frequency of a cable (is: half wave numbers in the cable length)

f_n is the natural vibration frequency of the related order of a cable

l is the free length or bending length of a cable

K is the proportional coefficient ($KN \cdot s^2$)

3.2 Monitoring Points Arrangement

3.2.1 Layout Principles

The deformation monitoring networks are divided into base point, work datum point and deformation observation point. The layout should follow the principles below:

(1) Base point: shall be in stable and reliable positions outside the deformation influential area, and each bridge should have at least three base points;

(2) Work datum point: Shall be in a rather stable and user-friendly position;

(3) Deformation observation point: Shall be set up in the position where can reflect the detection deformation characteristics or a test section.

3.2.2 Measuring Points Layout

(1) The Plane Control Network

Select positions which can reflect the detection plane characteristics or three points on the test section as measuring points;

(2) Elevation Control Points

Select positions which can reflect the control elevation characteristics or two points on the test section as measuring points.

(3) The Bridge Deck Line

The bridge deck line monitoring points makes full use of historical monitoring points and sets up additional liner measuring points for those unsatisfied ones, specific arrangements of measuring points are as follows: the bridge deck line monitoring is only in view of the main line. Linear observation points in longitudinal direction of each corresponding cross-section and main span, L / 4, supporting point and other control sections were set up. And according to the requirements of the stationing spacing is not more than 20 m, additional linear observation points were added.

Linear observation points are set on the bridge to the right or left medial part of bridge deck against a wall at the bottom of the picture, the right side of the median fence outside concrete base side decorate. According to the bridge longitudinal, it was divided into three measuring lines (L, Z, R line).They are left, middle and right lines. The whole bridge has 312 deck linear observation points. The observation points uses stainless steel round head nail, implant inserted bar glue after drilling hole with churn drill and identified with red paint. Arrangements of measuring points are shown in Figure 2 and Figure 3:

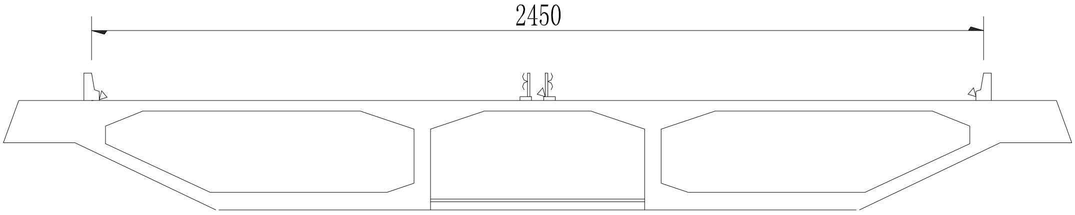

Figure 2. The deck arrangement of measuring points in alignment profile (unit: cm)

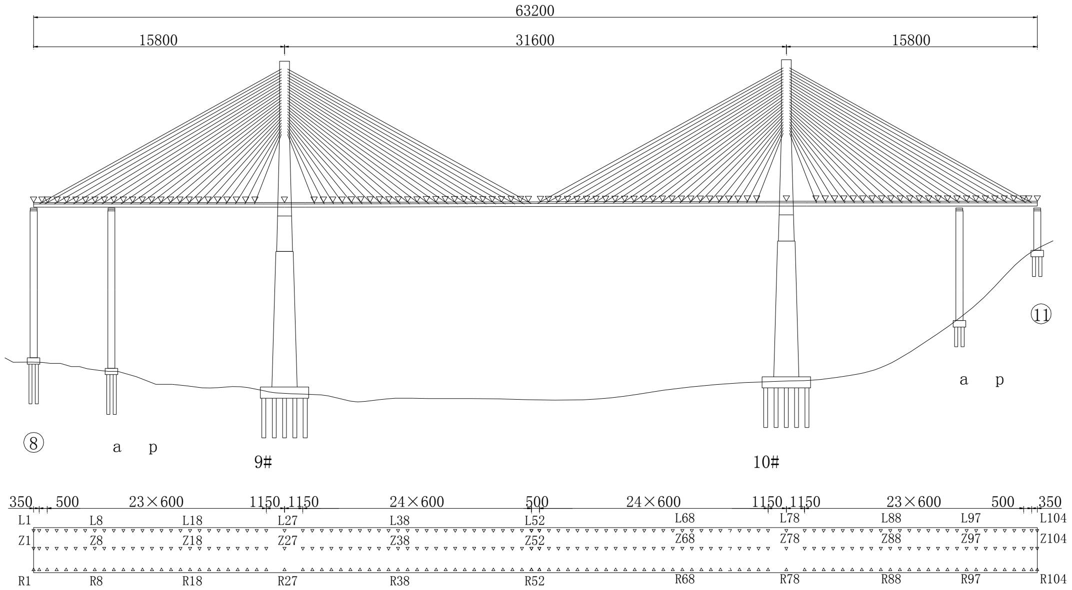

Figure 3. The deck arrangement of measuring points in alignment profile (unit: cm)

(4) The Deformation of Cable Tower

In this deformation monitoring, there are 8 deformation observation points on the cable tower and 4 points on each pylon which arrange at the top and the middle of the pylon. Arrangements of observation points are shown in Figure 4.

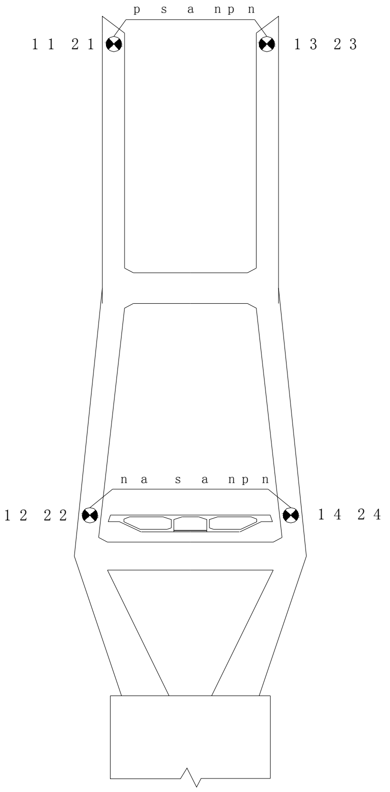

Figure 4. The arrangement of measuring points in cable tower deformation

(5) The Deformation of Expansion Joint

In this expansion joint monitoring, every 1 observation section was set at each expansion joint of the main bridge. And observation sections were set outside of the deck when laterally and each observation section has 2 observation points, a total of 4 observation sections, 8 observation points. Arrangements of measuring points are shown in Figure 5.

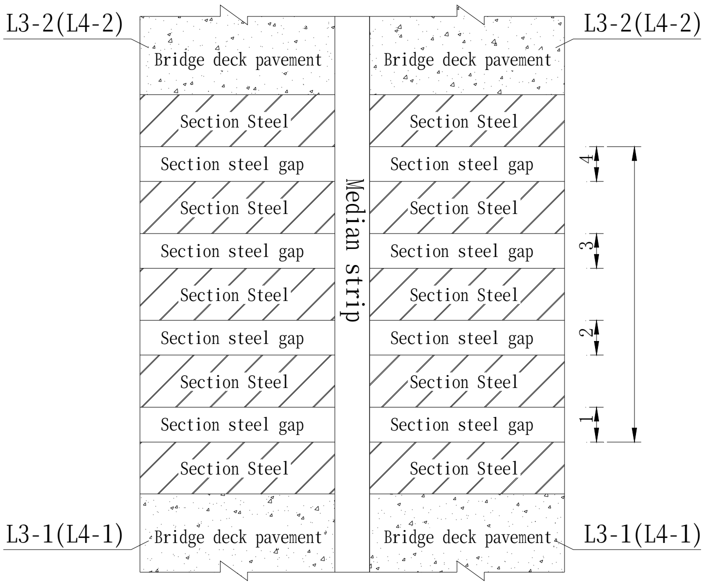

Figure 5. Monitoring point arrangement on expansion joint deformation

(6) Cable Force

In order to pick up vibration signal of stayed cable under environment excitation accurately, cable force test points should be chosen in the part of a larger vibration amplitude of the cable stayed and the maximum to avoid the influence of damper and steel thimble. According to the test conditions, the cable force measuring points is close to the PE thimble of the bridge deck, specific arrangement of measuring points are shown in Figure 6.

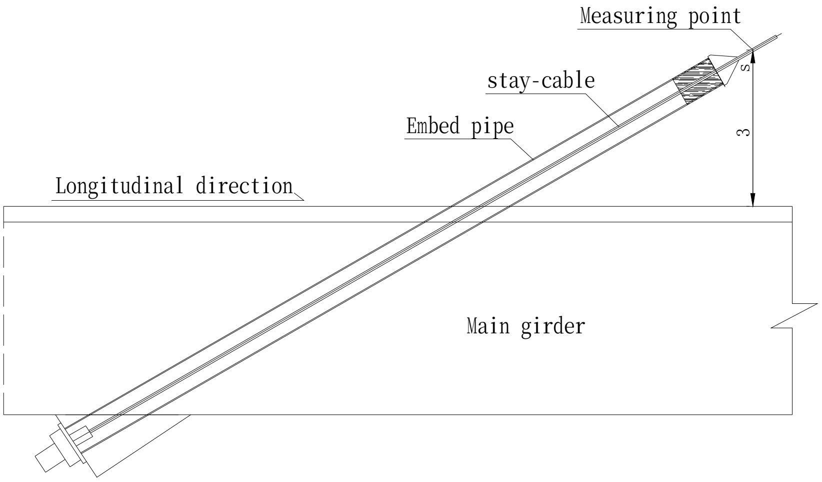

Figure 6. The arrangement of testing points in cable force

4. Monitoring Results and Analysis

4.1 Theoretical Calculation of Deformation Monitoring

According to the material parameters and usage of the bridge, using the FEA software calculates the theoretical value of the bridge deformation. Stayed cable adopts truss element to simulate, and the main girder adopts beam element to simulate. Stay-cables, the girder and cable pylons adopt rigid connection. The master nodes are respectively set in the main pylons and the girder, the main tower beam is simulated according to actual condition, the main girder diaphragms adopt the equivalent load to simulate, a total of 865 nodes, 648 units. The main types of bridge load in the model include dead load, temperature load, cable force, wind loads, etc. Discrete graph structure model is as shown in Figure 7.

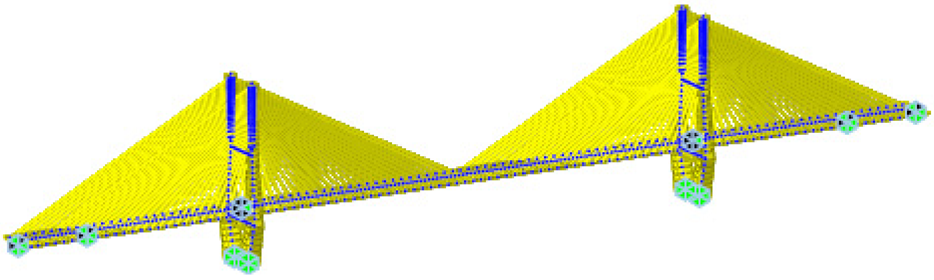

Figure 7. discrete graph structure model

Through the model analysis, theory values of the geometry of bridge deck, tower deformation, expansion joint deformation and cable force can be obtained.

4.2 Contrastive Analysis of Theoretical and Measured Values

After the theoretical results obtained by using finite element analysis software, the measured values of the bridge deformation can be obtained according to the contents and methods of monitoring the bridge. After obtaining theoretical and measured deformation values, then the measured values with calculated values can be compared. Deflection of the bridge, tower vertical displacement, tower deviation, expansion joints deformation, cable force comparative analysis results are as follows.

4.2.1 Contrastive Analysis of the Bridge Deck Linear Deflection

Contrastive analysis of two measurement results, “the measured deflection” is the “second phase (December 2012) the relative elevation data” subtract “the first phase (September 2012) the relative elevation data”. A positive value indicates up-flexion, a negative value indicates down deflection. Theoretical value extracted from the finite element program structural model. Comparison of measured deflection and theoretical deflection is as shown in Figures 8-10.

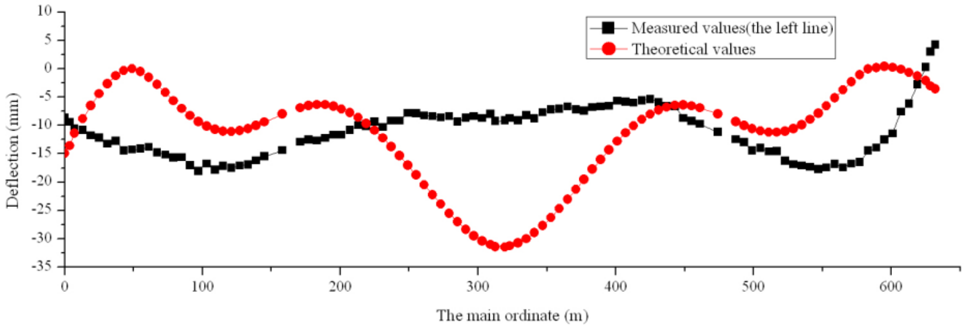

Figure 8. The measured deflection and the theory of the left line of bridge deck alignment deflection comparison chart

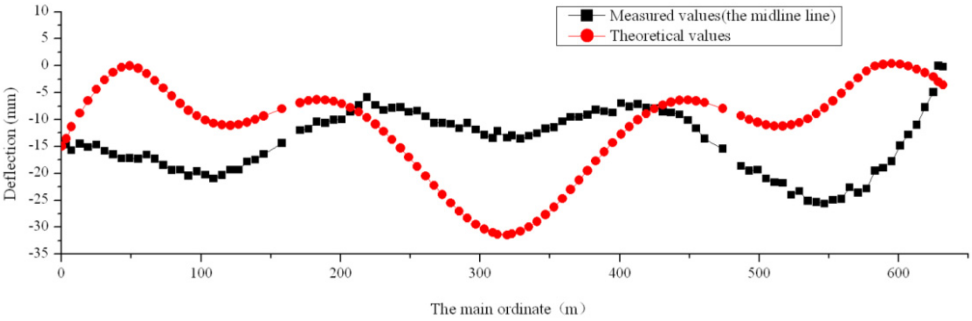

Figure 9. The measured deflection and the theory of the center line of bridge deck alignment deflection comparison chart

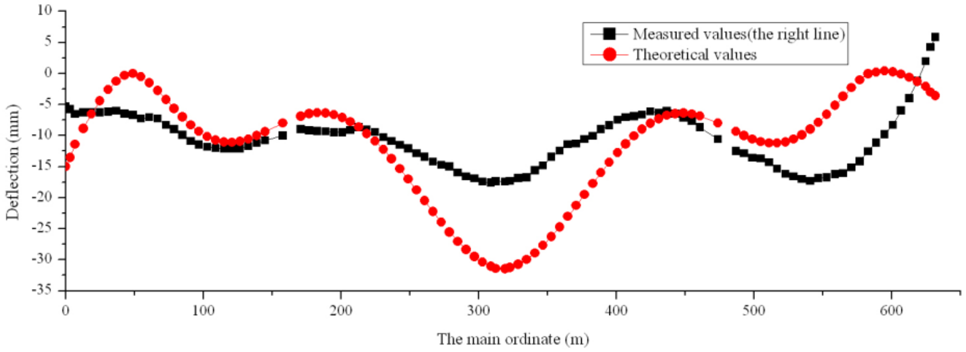

Figure 10. The measured deflection and the theory of the right line of bridge deck alignment deflection comparison chart

Thus it can be seen that the deflection of the bridge deck, the left side of the maximum deflection occurs in the cross-section 0.445L of the 10# span, deflection value is 18.06 mm, 8.72 mm larger than the theoretical value. The middle of the maximum deflection occurs in the cross-section 0.664L of the 12# span, deflection value is 25.61 m, 17.75 m larger than the theoretical value. The right side of the maximum deflection occurs in the cross-section 0.609L of the 12# span, deflection value is 17.59 mm, 8.36 mm larger than the theoretical value.

4.2.2 Contrastive Analysis of the Results of the Tower Vertical Displacement

In order to understand the situation of tower settlement in monitoring period and its influence on the deck line, the vertical displacement of the bridge were measured. "Measured Vertical Displacement of the Tower" stands for "Relative Elevation of 1st Phase subtract Relative Elevation of 2nd Phase". Calculated Vertical Displacement is the theoretical value in consideration of the overall temperature drop and shrinkage and creep. "The vertical displacement of the Tower" as a negative value indicates downward deformation. Contrastive results are shown in Table 1.

Table 1. Test result of Cable tower vertical deformation (unit: m)

No.	Measuring Point	Location	Relative Elevation of 1st Phase	Relative Elevation of 2nd Phase	Measured Vertical Displacement of the Tower (10^{-3})	Calculated Vertical Displacement (10^{-3})
1	T1-2	Middle of 9# tower of left bridge	111.586	111.5741	-11.89	-14.27
2	T1-4	Middle of 9# tower of right bridge	111.6264	111.6149	-11.47	-14.27
3	T2-2	Middle of 10# tower of left bridge	118.2727	118.2585	-14.19	-15.34
4	T2-4	Middle of 10# tower of right bridge	118.2874	118.274	-13.46	-15.34

As can be seen from test results of the main bridge tower observation point, under the conditions of cooling 16.7 °C, the central position of the pylon of 9# tower's vertical deformation is 11.89 mm, 14.27 mm less than the theoretical value, the central position of the pylon of 10# tower's vertical deformation is 14.19 mm, 15.34 mm less than the theoretical value. The above analysis shows that the measured vertical displacement of each main bridge tower is less than the calculated value, so that we can make a preliminary determine that there was no obvious settlement deformation of each main tower during the initial monitoring period.

4.2.3 The Tower Deviation Comparison Analysis

In order to get the status of bridge tower deformation during monitoring period, measurements of the bridge axial displacement were taken "Measured Axial Displacement" is the value that the measuring point displacement converts to the axis of the bridge based on the first and the second phase measured data; "Theoretical Axial Displacement" is the theoretical calculation value which in according with the test conditions including the overall cooling, cable force change, wind load effects, and the shrinkage and creep value; Positive values in "Axial Displacement" means deviating to the north, while negative value to the south. The theory and the measured results are shown in Table 2:

Table 2. Comparison on theoretical and practical results of Cable tower deviation (unit: mm)

No.	Measuring Point	Location	Measured Axial Displacement(10^{-3})	Theoretical Axial Displacement(10^{-3})
1	T1-1	Top of 1# tower of left bridge	29	33.68
2	T1-3	Top of 1# tower of right bridge	27	33.78
3	T2-1	Top of 2# tower of left bridge	-28	-33.69
4	T2-3	Top of 2# tower of right bridge	-27	-33.8

According to the test results of main tower observation points and under the condition of temperature cooling is 14.3 °C, 9 # tower location along the bridge to the river's side tilts 29 mm, 33.68 mm less than the theoretical value; 10 # tower location along the bridge to the river's side tilts 28 mm, 33.69 mm less than the theoretical value. Tower deviation measured value is less than the theoretical calculation shows that the deformation is in normal range.

4.2.4 The Expansion Joint Deformation Comparison Analysis

By comparing and analysis the measured value and theoretical value of 4 expansion joints clearance on both the left and right sides of the bridge with total station and steel tape, the results are shown in Table 3.

Table 3. Comparison on theoretical and practical expansion joint clearance of deck (unit: mm)

Side	Expansion Joint No.	Total Station Measured Deformation	Steel Tape Measured Deformation	Theoretical Deformation
The left bridge	L3#	41	41	50.91
	R3#	42	42	50.91
The right bridge	L4#	33	34	48.05
	R4#	35	35	48.05

According to the measuring results of expansion joints that under the condition of temperature cooling 14.3 °C, the width of each expansion joints is in expanding condition, the expansion joints of the main tower 3# expanded 42 mm, 50.91 mm less than the theoretical value while the expansion joints of 4 # 35mm, 48.05 mm less than the theoretical value. The measured expansion deformation value is less than the theoretical value. Comparatively speaking, the expansion joints of 3# are larger than 4#, which means that every expansion joint is in good working condition during the monitoring period.

(5) Cable Force Test Results and Contrastive Analysis

In order to know the change of cable force, make a test for each cable, the measured cable force and the designed cable force comparison results are shown in Figures 11 ~ 13.

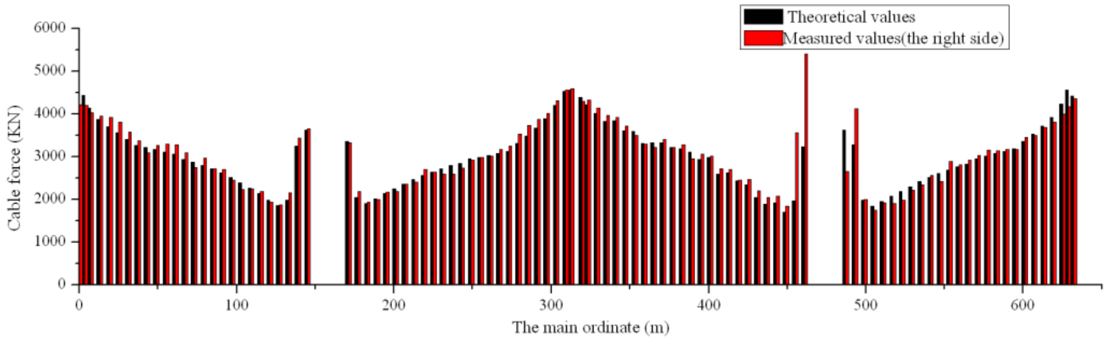

Figure 11. The right side measured cable force and the design force comparison chart

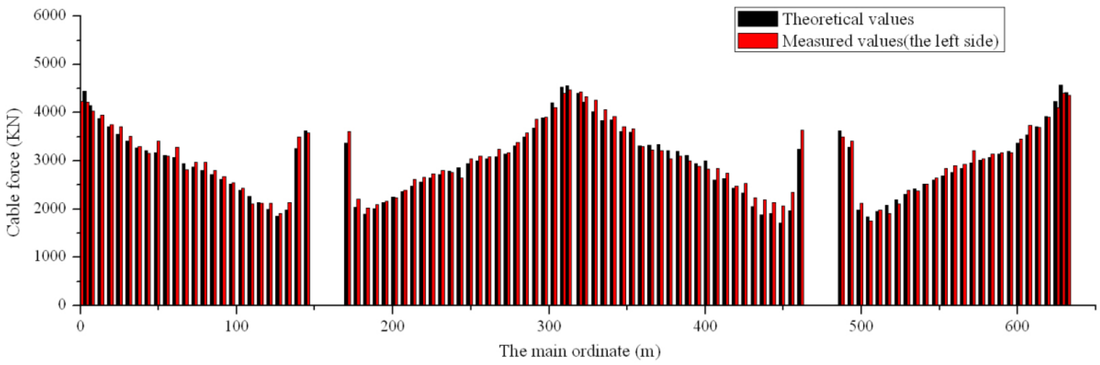

Figure 12. The left side measured cable force and the design force comparison chart

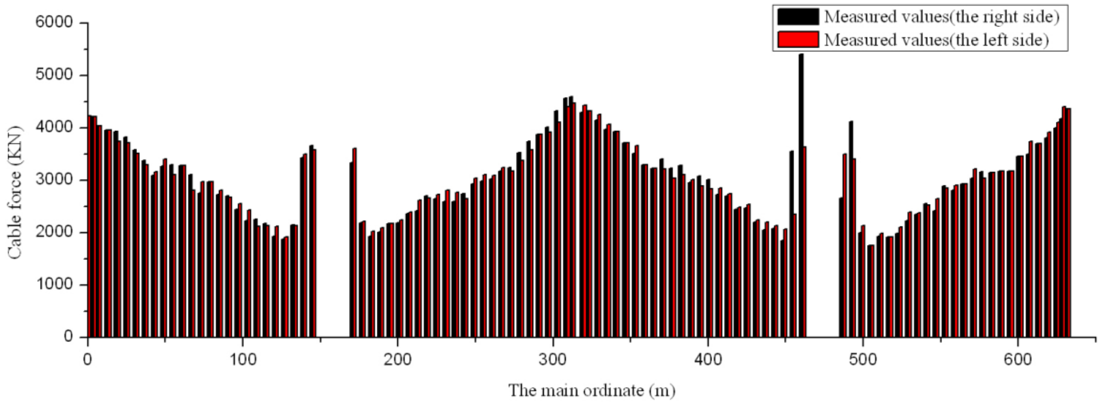

Figure 13. The left and right side measured cable force comparison chart

Figures 11 -13 show that the regularity of stayed-cable force on the left and the right side of the large bridges basically the same. The measured values and designed values of the two phases completed accord well with each other.

5. Conclusion

Through the results of contrastive analysis by field measured data and the theory data calculated by finite element software, conclusions can be got as follows:

(1) We can know from the bridge deck deflection testing results and deflection analysis diagram: change rules of three measured deflection curves which correspondently in the left, middle and right sides is the same with theoretical curve. Measured deflection values and the calculated values of each measuring point are in or near the theoretical value scope, deformation belongs to the normal range;

(2)The vertical deformation values of the middle part in pylons are less than the calculated values. Thus a preliminary determination that no obvious settling deformation of each main tower occurred during the monitoring period can be made;

(3) The top of the two pylons along the bridge to the river's side direction deviations are less than the calculated values, which shows that the deformation is in normal range;

(4) Under the condition of the site environment, the measured values of bridge expansion joint deformation are less than the calculated values, and the expansion joint is in good working condition.

(5) The regularities of dead load cable force on both left and right sides are basically the same. The measured values and designed values completed accord well with each other.

Currently, the bridge is only under the condition of no moving load monitoring. We measure structure performance by static deformation of the structure. We suggest to establish health and safety monitoring system at an appropriate time, using modern sensor technology to real-time monitor the structural response parameters of bridge operation stages under various environment (dynamic characteristics and vibration, dynamic strain and dynamic deflection), acquire all kinds of information which can reflect the status of structure and environmental factors and make a comprehensive evaluation of bridge structure conditions.

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