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Research on Construction Monitoring Techniques for Cable Replacement of the Cable-Stayed Bridge

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Abstract: Due to various reasons, some cable-stayed bridges require the replacement of part or all stay cables after operating for a period of time. In this study, based on some engineering practices of stay cable replacement, the condition of bridge structure before replacement is analyzed with Finite Element Analysis method for plane member system. The theoretical calculations, cable force measurement, replacement methods and process monitoring for cable replacement are introduced to find out the key technical problems. From the specified bridge monitoring practices, we suggest monitoring cable tension and the main beam alignment during the process of cable replacement, to make sure the cable-stayed bridge reaches its design conditions.

Keywords: Cable-stayed Bridge, cable tension measurement, construction monitoring, cable replacement, finite element analysis

INTRODUCTION

The cable-stayed bridge is a common type of bridges in modern world. Because most parts of the stay cables in a cable-stayed bridge are exposed outside of girders and towers, the thin cables under high stress are very sensitive to rust. Once the cable were rusted for improper way of antirust, its effective section area will decline rapidly, even be broken. Then for security reason part or all stay cables have to be replaced far before design life is reached (Yonggang, 2002). Beside that, after a period of operation, due to stay cable relaxation, concrete shrinkage and creep, the dead load internal forces of the structure will certainly deviate from the ideal state of the design and the bridge alignment will also deviate from design. Because the live loading changes on quantity and position, it is not possible to adapt it at any time to a finished bridge, but to adapt the dead load internal force by adjusting cables. Through the process of able replacement or cable adjustment, the bridge alignment reaches or returns to its design (Jishun and Pu, 2005). Some famous bridge, including Bridge Maracaibo in Venezuela, Bridge Kohlbrand Estury in Germen, Bridge St. Nazaire in France, Bridge Paso-Kennewick in United States, had replace their stay cables for improper protection (Wentao, 2006). Those bridges in China, including Bridge Haiyin in Guangzou, the Highway Bridge over Yellow River in Jinan, Bridge Minwei over River Min and Bridge Tongzilin over River Yayanjiang in Sichuan,etc., have changed all cables because of rust problems. In the last fifty years, hundreds of cable-stayed bridges have been built in all over the world, which require more projects on cable replacement with the time goes on. How to perform better simulations on the cable tension and main beam alignment deviation before replacement and which techniques and methods of monitoring to be taken during construction, are the key technical problems for cable-replacement project of the Cable-stayed Bridge.

Overview of the specified bridge: The specified bridge in this study is a prestressed concrete cable-stayed bridge with double towers and double cable planes. Its span length is 52+66+240+66+52 meters, main beam sections is a single-box three-cell broad box, of 14.10 meters wide and 2.40 m high and using concrete C40. There are 56 pairs of stay cable units distributed like a fun and each unit includes two or four cables which connect to one lifting point. The towers have a ladder shape, with cross-bolt-type anchoring system.

After ten years of operation this bridge took a full scale examination, to found that it ware in a serious condition. The PE covers on cables were in a serious situation of cracking, fracture and damage. There were broken wires in 33 cables, 17.2% of total cable number. The most damaged cable is the 13D cable of 12^{th} tower, with 33 broken among 61 Ø5 steel wires. And 37 cables of 19.3% of total were found rusted spots in wires, 108 cables of 56.2% total were found rusted spots and corrosion pits. Only 14 cables, 17.3% of total, were in perfect status. The safety factor of single wire was 1.97 and according to the original design the maximum subsidence of bridge alignment reached 25 cm. After a careful risk assessment, a decision was made to carry

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out full replacement of the stay cables and to restore the design alignment. Cables will be replaced with 55~127×Ø5 high-strength low-relaxation twisted galvanized steel wire, whose standard strength is R_y^b = 1670 Mpa New PE cover is made of high density Polyethylene, with tensile strength greater than 20 Mpa, yield strength greater than 16 MPa.

ANALYSIS OF INTERNAL FORCES AND DEFORMATION

The aged stay cables have to be replaced to improve bridge's structural bearing capacity. Cable tensions are to be optimized to correct the deviation of bridge alignment and internal forces from design. To achieve them simultaneously, before replacement the alignment and stress state of whole bridge structure, especially the cable tension, should be analyzed to determine the adjust value of each cable's tension and to access the consequence of adjustment. So a stay cable replacement model was developed to establish the initial point and testified and adjusted with data of alignment and cable tension before operation. Basing on this model, the whole process of cable replacement was analyzed (Weiping *et al*., 2010).

Analysis overview: The software of Plane Bridge Structure Analysis System (PQJF 3.2) is used for calculation during the replacement. The bridge was constructed by cantilever casting, experienced several times of system conversion and reached prior-replacement state after ten years of operation. In order to simulate the structural condition before and during the replacement, we superimposed the multiple conditions of different working period since the beginning, to complete the accumulation calculation of internal forces and displacement. After a serious of adjustments of parameters, the conditions calculated from model were very closed to actual conditions. Because the bridge conditions changes continuously during cable replacement and cable tension adjustment, the analysis of internal forces change and displacement has to be calculated and be output separately for each working conditions.

Model of analysis: In this model of analysis, the structure of whole bridge is taken as object for structure analysis of cable replacement. After discretization, there are 468 plane beam elements and 467 nodes, including 116 slave nodes, shown in Fig. 1. Based on the host-slave node relations, we have established the correct deformation relationship between end point of stay cable and tower node and between main girder nodes and bearing nodes. In this model, the connection between tower and auxiliary pier is set to be a dead joint and a hinge mount is set to restrict vertical movement after the main beam's largest cantilever is in position. 2~4 stay cables which connect to the same main girder section are treated as one member. During the grouting of 0^{th} block and tensioning of 27^{th}, 28^{th} stay cable, a temporary support was set under the main girder, which is modeled as two weightless hinged rigid members. This support should be repealed from model to calculate the tensioning process of 27^{th} and 28^{th} cable.

In a cable-stayed structure, a cable is always treated as a flexible beam. In this model, a cable is treated as a axial tension and compress member, whose tension is loaded by tower and girder. Shown in Fig. 2, the tension are a pair of concentrating force along the axial direction of the beam and a corresponding pair of reacting force to girder and tower.

Because the bridge has a hyperstatic structure, additional force at completion state should be calculated with consideration of temperature's effect. Temperature difference of system is set to ±20°C and of cable and main beam, including up-down difference on main beam and left-right difference on tower, is ±5°C. The cable replacement process includes 45 construction periods, 1 shrinkage-creep period, 44 cable-replacement periods and 3 cable-adjusting periods (including two periods during the replacement and one period after all replacement). The initial tension force in stay cables and the longitudinal prestress on up and down edges of main beam are based on the completion drawing (completion materials). The calculations of live loading are based on same load standard in design, automobile - 20, trailer-100, crowds -3.5 kN/$m^{2.}$

Effects of nonlinear structure: In a prestressed concrete cable-stayed bridge, the relation between displacement and internal force is nonlinear, which makes structural analysis very complex. There two kinds of nonlinearity:

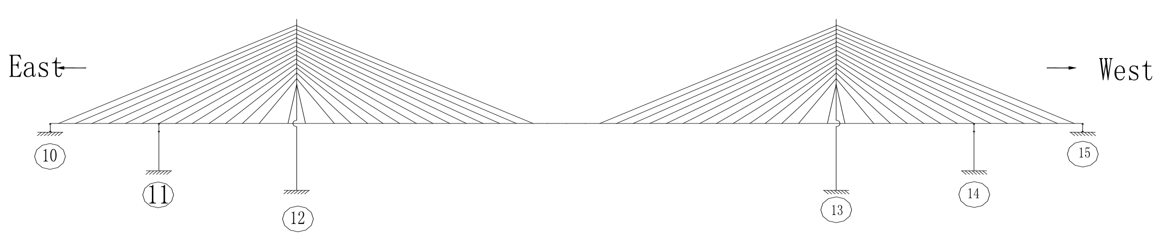


Fig. 1: Structure discrete model of the cable-stayed bridge

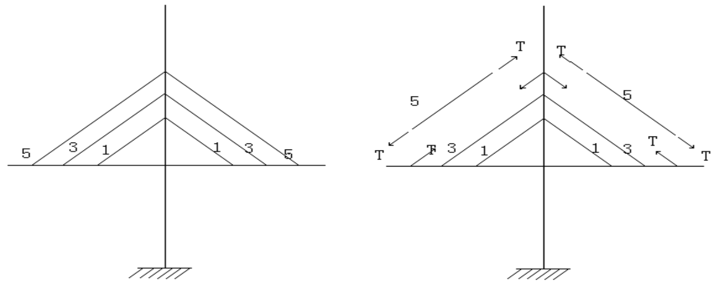


Fig. 2: Tension effect on stay cables

Table 1: Comparison of cable tension of 12th tower

Cable SN.	Theoretical Tension(KN)	Cable breakage load (KN)	Upstream side: Upper measured (KN)	Upstream side: Measured/calculate (%)	Upstream side: Cable safety no.	Downstream side: Down measured (KN)	Downstream side: Measured/calculated (%)	Downstream side: Cable safety
83(2)	2341.0	7571	3842.3	164.1	1.97	3712.5	158.6	2.04
85(4)	1896.6	5717	2028.0	106.9	2.82	2057.0	108.5	2.78
87(6)	2107.9	7602	2194.5	104.1	3.46	2230.6	105.8	3.41
89(8)	2333.8	8355	2248.1	96.3	3.72	2308.0	98.9	3.62
91(10)	2486.8	8669	2407.5	96.8	3.60	2400.7	96.5	3.61
93(12)	2613.2	8795	2425.5	92.8	3.63	2457.6	94.0	3.58
95(14)	2706.0	8795	2536.3	93.7	3.47	2509.6	92.7	3.50
97(16)	2846.3	9172	2581.3	90.7	3.55	2626.6	92.3	3.49
99(18)	2966.7	9550	2720.9	91.7	3.51	2714.3	91.5	3.52
101(20)	3051.5	9550	2700.5	88.5	3.54	2722.5	89.2	3.51
103(22)	3144.6	10681	2854.0	90.8	3.74	2853.3	90.7	3.74
105(24)	3153.6	10053	2900.6	92.0	3.47	2939.6	93.2	3.42
107(26)	3348.8	12942	3470.6	103.6	3.73	3437.4	102.6	3.77
109(28)	2008.6	5717	2153.0	107.2	2.66	2190.7	109.1	2.61

- Of material, caused by the uneven concrete
- Of geometry, caused by disproportional between displacement and internal force for dead weight reason

Using the Plane Bridge Structure Analysis System, 2 types of nonlinear coefficients are considered to calculate prior-replacement structure condition, while only one type of coefficient is considered to calculation during cable-replacement. To normal concrete beam units, their elastic modulus E is conversion elastic modulus. To cable units, their modified modulus is calculated with Eq. (1), with consideration of cable sag effect:

$$E_i = \frac{E}{1 + \frac{\gamma^2 l^2}{12\sigma^3} E} \tag{1}$$

where,

E_i = The modified modulus
E = Modulus without consideration of cable sag effect which equals modulus of the cable steel
γ = The density of cable
σ = The cable stress
l = The length of cable's horizontal projection (Guomin and Yuanchang, 1996).

Calculation results: Based on the analyses, we calculated the internal forces for each construction period. The comparison of calculated cable tension and measured actual cable tension are shown in Table 1 and the cable broken force has been deducted the effect of broken wire.

In Table 1, the calculation results basically match the measurements for cable tension before replacement. The measurement may be affected by the broken wires and rusts in cable.

MONITOR OF CABLE TENSION IN CABLE REPLACEMENT

Tower, beam and cable are the main stressed members and should be monitored during the construction of new bridge. The bridge has a special structure, multiple cables connecting to one connection spot. Basing on the result form calculation, we find that the changes of tension on main beams and towers are minimal, so we won't monitor the tension on main beams and towers. The working condition of stay cable is one of the key evaluation indexes of the normal operation of a cable-stayed bridge. It's important to measure the tension force on cables precisely, especially when the cables are being replaced. Because the cable tension is the only factor to be adjusted during the replacement, in order to maintain or improve the operation level of the bridge, cable tension measurement is the first step to be done. Currently the engineering methods to measure the tension force include oil pressure gauge reading method, pressure sensor testing method and the most popular frequency vibration method.

- **Method of frequency vibration:**
  Differential equation method: Cable tension force is calculated from its vibration frequency based on principle of vibration of chord (Jiajun and Guanyong, 1990).

To a tensed stay cable with neglected flexural rigidity, its dynamic equilibrium equation is written as:

$$\frac{W\partial^2 y}{g\partial t^2} - T\frac{\partial^2 y}{\partial x^2} = 0 \tag{2}$$

where,

- y = The transverse coordinate which perpendicular to the cable force
- x = The vertical coordinate along the force
- w = The weight of cable per unit length
- g = The gravity
- T = The tension force to calculate
- t = Time

Assuming the ends of cable are stable, from Eq. (2) we have:

$$T = \frac{4WL^2}{n^2 g} f_n^2 \tag{3}$$

where,

- f_n = The n-th natural frequency
- L = The cable length
- n = The order of the vibration system

To a tensed stay cable with flexural rigidity, its dynamic equilibrium equation is written as:

$$\frac{W\partial^2 y}{g\partial t^2} + EI\frac{\partial^4 y}{\partial x^2} - T\frac{\partial^2 y}{\partial x^2} = 0 \tag{4}$$

where, *EI* is the flexural rigidity. If the two ends of the cable are hinged, from Eq. (4) we have a simpler solution:

$$T = \frac{4WL^2 f_n^2}{n^2 g} - \frac{n^2 EI\pi^2}{L^2} \tag{5}$$

If the two ends of the cable are stable, we have another solution as:

$$2\alpha\beta(1-\cos\alpha L\cdot ch\beta L) + (\beta^2-\alpha^2)\sin\alpha L\cdot sh\beta L = 0 \tag{6}$$

If one end of the cable is stable and the other end is hinged, we have a solution as:

$$\beta\cdot\tan\alpha L = \alpha\cdot th\beta L \tag{7}$$

In Eq. (6) and (7), a = Elg/W, b = Tg/ W, $\alpha = ((b^2 + 4aw^2{}_n\text{-}b)^{1/2}/2a)^{1/2}$, $\beta = ((b^2 + 4aw^2{}_n+b)^{1/2}/2a)^{1/2}$, $\omega_n = 2\pi f_n$. To a cable with known W, L, and g, if its natural frequency f_n is measured precisely with the order n, the tension force is solved.

- Finite Element Method. If the flexural rigidity of cable cannot be neglected and the boundary conditions are too complex to calculate the tension force by solving equations, finite element method is the right choice. In this method, the stay cable is modeled as a plane structure and divided into numbers of elements and then the element stiffness matrix is built with geometric stiffness, to calculate with frequencies measured from filed (Wentao, 2006).

Influence factors of vibration frequency:

- **Flexural rigidity:** The existence of flexural rigidity will enhance the vibration frequency of the cable. So if it is neglected, the frequency calculated from equations will be bigger than its real value. However, flexural rigidity has limited effect on calculation and its impact declines with the increase of cable length. To a cable with normal length, the error caused by flexural rigidity is about 2% to 3%, up to 5% -7% for particularly short cable. To eliminate this error, the analytical expression for flexural rigidity or finite element method will be used during the calculation of cable tension force.
- **Cable sag:** In the cable vibration analyses in last subsection, the cable is modeled as tensed arch without sag. During the static analysis of cable tension, Li Guohao introduced a dimensionless parameter *K* which is defined as:

$$K = H/\beta \tag{8}$$

where, $\alpha = \sqrt[3]{W^2L^5AE_S/\ 24L^3{}_S}$, $\beta = (W^2L^5AE_S/24L^3{}_S)^{1/3}$

- H = The horizontal part of the tension force,
- L_S = The horizontal projection length,
- W = The weight per unit length,
- A = The sectional area,
- E_S = Elastic modulus and
- L = The length of cable (Guohao, 1996)

The result of static analysis shows that, there are a linear relationship between tension force and cable length without consideration of cable sag if K is greater than 1.5. This conclusion only meet with the static property and whether it fits dynamic analysis is known.

Basing on the analysis of frequency with K, we find that cable sag has a obvious effect on the base frequency. If we want to restrict the effect less than 5%, the value of K must be greater than 2.5. If sag have a small effect on the high-order frequency (4^{th} or higher), the effect is smaller than 5% even if K is little than 0.5 and this result won't changes with the length of cable significantly. To a real cable-stay bridge, the value of K is always greater than 3, so cable sag can be neglected in the static or dynamic analysis of cable tension. While during the construction process of cable replacement the cable will be tensed in several periods. When K is less than 2 in the first or second tension process, cable tension force can be calculated with frequency of 4^{th} or higher order to reduce the effect from cable cag (Zhi and Zhiyong, 1997).

Absorber: To a stay cable, the absorber will restrict the free length and increase the natural vibration frequency. This effect will much obvious to short cable. Usually the effect of absorber on precision of cable tension force won't bigger than 5% if the cable length is greater than 150 meters. It is complicated to describe or analyze absorber's effect on cable frequency. The only realistic way is, we measure each cable's frequency change after the absorber is installed, then we can determine the restrict effect of absorber. Here f_1 is the cable's base frequency and f_2 is the basic frequency after the installation of absorber, l_1 is the real cable length, then the equated length l_2 can be calculated as:

$$l_2 = (f_1 / f_2) l_1 \tag{9}$$

After all equated cable lengths are calculated, tension forces in the cable with absorber can be calculated with the equated lengths and frequencies measured from real bridge.

Method of cable replacement: In the plan of whole bridge cable replacement, the guiding principle is, antisymmetric to two towers, symmetric to single tower. At each period, four cable with same cable number on two towers will be replaced. The cables next to the replaced cables will be monitored to calculate their tension forces at real time. Situation will be compared, analyzed, assessed and feedback to the design unit. The result of real-time monitor shows that, after one cable was removed, the tension force on the neighbor cables only increased 10% to 20%. In each day of the replacement process, 8 cables were replaced and then cable tension forces were measured at the same period. The detailed monitor sequence is shown in Fig. 3.

Determining cable tension of specified bridge: Frequency vibration method is used to determine the cable tension during the cable-replacement of specified bridge. First, the vibration signal was picked up by the acceleration sensors attached on the stay cable. Second, the signal was amplified and transmitted to data acquisition device. Third, data were processed for spectrum analysis with professional software on computer, to read the vibration frequency of each order. Finally, spectral analysis was done with software Dasylab. The work flow is shown in Fig. 4. Based on the technical material from cable supplier, with the correction of cable elastic elongation under tension control, the equated cable length in Eq. (3) were calculated as:

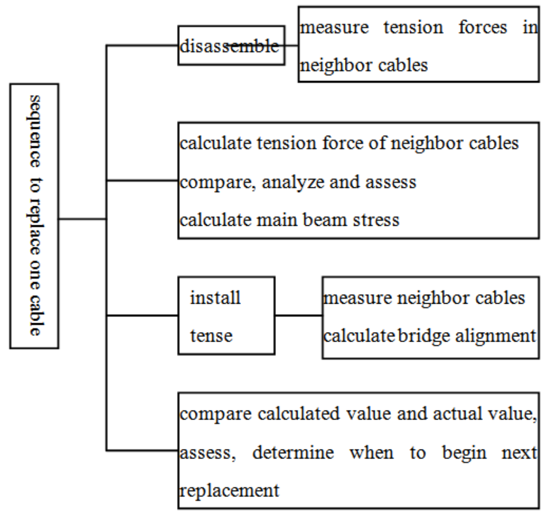


Fig. 3: Monitor sequence of cable replacement

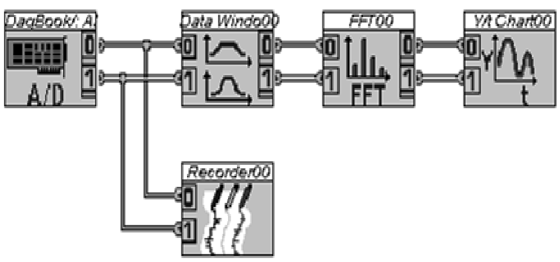


Fig. 4: Spectral analysis by software Dasylab

$$\Delta l_e = NL / EA \tag{10}$$

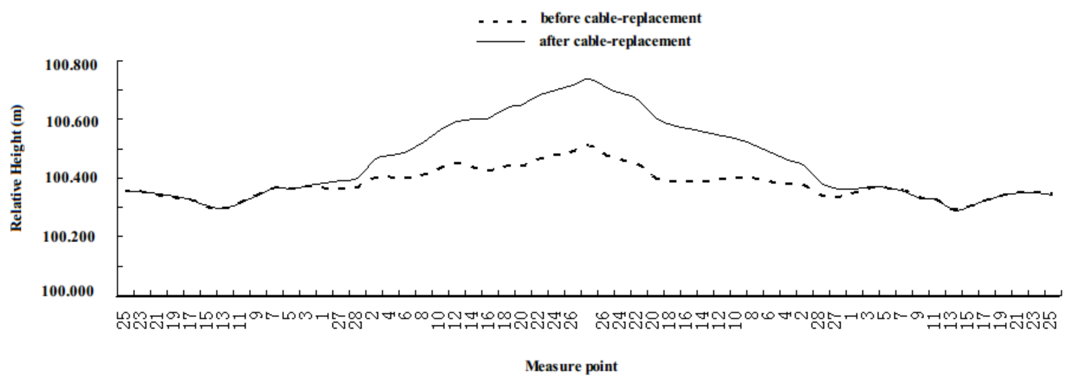
where,
N = The tension control force (kN)
L = The geometric length of cable (m)
E = Young's elastic modulus of steel wires which equals 195GPa
A = The section area of steel wire (mm^2)

Now consider the effect of cable sag. The value of K is 1.87, to the longest cables in this bridge, the 25^{th} and 26^{th} cable. In subsection 3.2, we know the vibration frequencies under 4^{th} order are free from the sag effect. Because orders of the frequency measured from cable were below or equal 3, we neglect the sag effect.

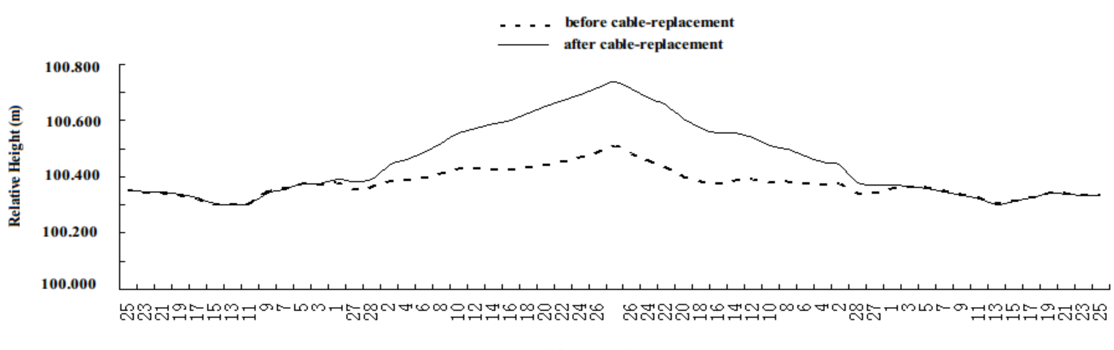
The cable tension directly affects the internal force and deflection of the main beam. So it's necessary to

Table 2: The comparison of design tension and actual tension in cables from 12th tower after replacement

		Upstream side		Downstream side	
Cable no	Design tension (KN)	Actual tension (KN)	AT/CT (%)	Actual tension (KN)	AT/CT (%)
1	1908.9	1834.5	96.1	1853.5	97.1
2	2044.8	1952.8	95.6	1958.9	95.8
3	1594.1	1598.8	100.3	1625.1	101.9
4	1699.6	1738.2	102.3	1742.1	102.5
5	1709.4	1767.5	103.4	1789.7	104.7
6	1866.2	1933.4	103.6	1925.7	103.2
7	1841.6	1882.1	102.2	1893.2	102.8
8	2052.3	2158.2	105.2	2171.9	105.8
9	1936.2	2025.3	104.6	2031.1	104.9
10	2179.8	2262.4	103.8	2260.6	103.7
11	1996.6	2080.5	104.2	2086.4	104.5
12	2261.1	2329.2	103.0	2333.2	103.2
13	2048.4	2136.5	104.3	2142.6	104.6
14	2306.1	2384.7	103.4	2387.9	103.6
15	2166.8	2221.0	102.5	2246.9	103.7
16	2388.0	2510.8	105.1	2519.3	105.5
17	2312.2	2423.2	104.8	2413.7	104.4
18	2465.1	2592.6	105.2	2603.1	105.6
19	2504.0	2646.7	105.7	2641.7	105.5
20	2556.5	2663.9	104.2	2666.4	104.3
21	2948.4	2913.0	98.8	2916.0	98.9
22	2871.3	2845.5	99.1	2805.3	97.7
23	3321.5	3182.0	95.8	3195.3	96.2
24	3093.4	3077.9	99.5	3068.3	99.2
25	3948.9	3881.8	98.3	3893.6	98.6
26	3504.7	3371.5	96.2	3340.0	95.3
27	1918.7	1863.1	97.1	1857.3	96.8
28	1934.6	1863.0	96.3	1888.2	97.6



(a)



(b)

Fig. 5: Comparison of main beam alignment before and after replacement; (a): Upstream side; (b): Downstream side.

perform real-time measurement on cable tension, to find the difference between the actual and the design value in time and to adjust in time. This will help to make sure the deviation of cable tension within certain precision range. In the monitor practice of specified bridge, artificial excitation or environment excitation were used in frequency vibration method. To determine the cable tension precisely, no operation on cable were allowed before the all cable's measurements were finished, including installing or disassembling absorber. And no vehicle went through the bridge. The comparison of design tension and actual tension is shown in Table 2. From this table, we know the result of cable-replacement meet the design.

Monitoring main beam alignment: It is also very important to monitoring the main beam alignment. In practice, we found that the main beam alignment of specified cable-stayed bridge were very sensitive to temperature. So all measurements should be taken in the same period of a day with same stable temperature. After cable-replacement, main beam alignment changed distinctively. At the span center the height raises 23cm and the main beam alignment were restored to its design state. The comparison of alignment is shown in Fig. 5.

CONCLUSION

The cable-stayed bridge is a good type of bridge for its novelty and beauty, strong spanning capacity, good wind resistance, safe construction and economy etc. But cable rusting and vibration fatigue are two great threatens and challenges to cable-stayed bridge's structure durability. The cable replacement has become one of the hottest research points. The successful experience of the specified bridge's cable-replacement monitoring has shown that, it is essential to make simulations precisely on the bridge condition before replacement and make good measurements on the cable tension and main beam alignment according to design requirements.

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