Finite Element Analysis of Mechanism Behaviour of Multi-tower Self-anchored Suspension Bridge

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Received 1 March 2014, www.cmnt.lv

Abstract

A finite element three-dimension space model is built by ANSYS based on the first multi-tower self-anchored suspension bridge in China. After that, the work aims at developing finite element analysis using backward and forward methods, discussing internal force of main bridge components in different construction stages. Then, linear change law of the main cable in different load conditions is analysed, and mechanism behaviour of this new structure in the whole construction is acquainted. Therefore, the work provides key force analysis for multi-tower self-anchored suspension bridge, making a good example for design and construction of similar bridges.

Keywords: Multi-tower Self-anchored Suspension Bridge, Mechanism Behaviour, Backward Analysis, Forward Analysis, Finite Element

1 Introduction

Multi-tower self-anchored suspension bridge is a geometric nonlinear flexible structure [1-5]. Its main cable construction process including saddle pre-bias, clamp installation and hanger tension will affect force and deformation of subsequent structure [6-9]. A finite element three-dimension space model is built by ANSYS based on Luozhou Bridge. After that, the work aims at developing finite element analysis using backward and forward methods, and discussing internal force of main bridge components in different construction stages. Then, linear change law of the main cable in different load conditions is analysed, and mechanism behaviour of this new structure in the whole construction is acquainted. Figure 1 shows the configuration of the main bridge. Fuzhou Luozhou Bridge is a self-anchored suspension bridge with a length of 496m, which is made of three towers and four spans. The bridge has continuous steel box girders with spans of 80m+168m+168m+80m, cable system of two cable-sides and rise-span ratio of 1/6. The main tower applies framework structure of reinforced concrete.

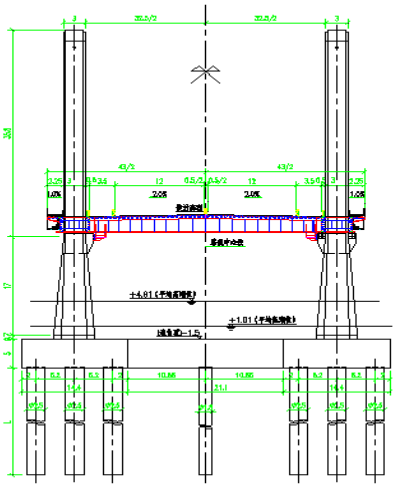

FIGURE 1 Configuration of the Main Bridge

2 Building finite element model

2.1 SELECTING ELEMENT

The accuracy of finite element simulation is determined by structure quality, stiffness, boundary conditions, etc. Link element Link10 is used to simulate the main cable and sling under tension only; link element Link8 to suspender; spatial beam element Beam44 to the main beam, cable tower and pier with large stiffness; beam element Beam4 to cable saddle and rigid crossbeam. Cable and temporary pier are simulated by link element Link10 with 6 degrees of freedom, large displacement and stress stiffness function. Besides, Link10 element can only bear simple tension or compression based on characteristics of bilinear stiffness matrix. Using tension option, the stiffness will disappear if Link10 element is under pressure, thus according with mechanical behaviour of the main cable and sling. Suspender uses link element Link8. It has similar characteristics with Link10 element except for special property of Link10. The cable is added with certain prestress to bear load. Each sling and suspender can be seen as a link element. The main cable can be divided into link elements by sling nodes. The elastic modulus of the main cable is corrected using equivalent elastic modulus and the original strain of main cable and sling (suspender) constraints. The main tower and stiffening girder apply spatial beam element Beam44. Beam44 element has characteristics such as bearing tension and compression load, and 6 degrees of freedom in each node. It is suitable to simulate asymmetric end and the structure in which end node is deviated from section centre. So, it can be used to simulate the main tower of variable section and the girder section with non-bidirectional axisymmetric structure. Table 1 shows parameters of the corresponding beam elements.

The main tower and girder are added with different section characteristics such as inertial moment and flexural rigidity according to different sectional areas. Beam4 can be selected to simulate fishbone rigidity crossbeam and cable saddle by calculating large deformation and stress hardening

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problems of homogeneous symmetric beam element. Enough rigidity is required to connect sling with rigid arm of girder in rigid crossbeam simulation. In cable saddle simulation, enough section area should be endowed (See Table 1).

TABLE 1 Element Parameters and Material Characteristics

Structure	**Element Type**	**Area(m2)**	**Elastic Modulus(Pa)**	**Density (kg/m3)**
Main Cable	Link10	0.047379	1.95×1011	7850
Sling	Link10	0.002729	1.95×1011	7850
Suspender	Link8	0.017671	1.95×1011	7850
Temporary Pier	Link10	-	Large Enough	-
Main Tower	Beam44	-	3.45×1010	2549
Upper Beam	Beam44	-	3.45×1010	2549
Corbel	Beam44	-	3.45×1010	2549
Girder	Beam44	-	2.06×1011	7850
Rigid Crossbeam	Beam4	0.1501	2.06×1014	7800
Cable Saddle	Beam4	100000	2.06×1011	2500

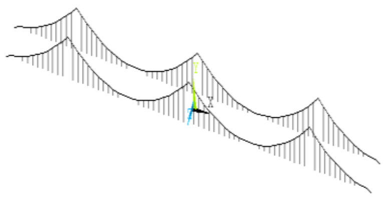

FIGURE 2 Model of Main Cable and Suspender (Sling)

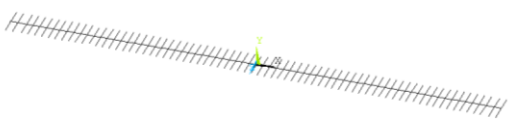

FIGURE 3 Fish-bone Girder Model

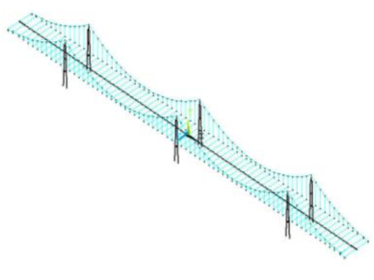

FIGURE 4 Three-dimension Finite Element Model of Main Bridge

In multi-power self-anchored suspension bridge, the girder should be set up at first. Before sling installation, temporary buttress requires enough bearing capacity. Then the girder is gradually separated from the temporary buttress in sling installation. In finite element simulation, temporary buttress is defined as ideal elastic-plastic element only under pressure or contact element. Boundary condition is changed to simulate quit of temporary buttress. Considering support of temporary buttress to the girder, the ideal elastic-plastic element Link10 is selected to meet the requirement of bearing capacity of buttress.

2.2 BOUNDARY PROCESSING

It is a complicated process to simulate boundary restrain and element connection of multi-power self-anchored suspension bridge. In finite element model, this process is usually achieved by coupling, consolidation, hinge joint, spring, etc. The tower and buttress bottoms are set as consolidation form of all degrees of freedom; the common nodes of tower and beam at main tower abutment is conducted with DOF coupling, and the corresponding nodes of the girder at side pier abutment is restrained according to actual situation; the common nodes are used on the joint of main cable and stiffening girder; the main cable saddle is fixed on the top of the main tower by roller support, and the DOFs in the whole directions are restrained except for the longitudinal direction.

2.3 MODELLING

The whole bridge model has 1087nodes and 1210 elements, ignoring the influence of bottom structures such as basic and side pier. The beam elements of the main tower and the girder are separately divided at an interval of 1 and 1.75 m, with some details refined; the nodes are set up by dividing link element of the main cable at the interval of slings; based on fish bone girder model, the corresponding rigidity and mass of bridge floor system are concentrated on the nodes of fish bone, and the suspender (sling) nodes are connected with rigid arm element. In model calculation, the nonlinear factors caused by the original stress of structure, sag effect and large displacement should be considered to simulate mechanism behaviour of multi-power self-anchored suspension bridge.

3 Nonlinear numerical solution

3.1 FORM-FINDING OF THE MAIN CABLE

To determine the original strain of cable, the iterations for form-finding will not stop until the displacement of cable system and the horizontal forces imbalanced on both sides of top tower of the main cable under dead load are not more than the allowable value. The shape of spatial main cable to meet restrain and balance boundary conditions as well as configuration of the cable is found to achieve the corresponding coordinates and prestress value.

In nonlinear solution of multi-power self-anchored suspension bridge, the spatial form of the cable should be found at first. From-finding is a complicated iterative process. ANSYS applies the command UPGEOM to achieve iterations of cable coordinates. If the largest change value of displacement calculated by iterations meets the requirement, then form-finding will be finished. If the given main cable shape is endowed with original strain caused by dead-weight, then the displacement change will be zero after iterations in the ideal condition. In actual condition, none of the displacement changes of the main cable got by calculation are zero because of nonlinear influence of the original stress.

3.2 NONLINEAR ANALYSIS

According to dead weight of the cable, the main cable of multi-power self-anchored suspension bridge has certain rigidity achieved by starting stress stiffness in solution. The high stress in plane caused by dead weight has a great influence on rigidity of the cable out of plane, namely stress stiffness [2]. ANSYS applies command STTIF, ON to correct the main stiffness matrix of structure, thus achieving the geometric nonlinear influence of the original stress to the cable [3]. In self-anchored suspension bridge with no cable, the stress stiffness is remarkable. Because of flexibility of cable system, the bridge can be prestress structure, which bears the load when weight rigidity provided by the original stress based on dead weight of the main cable is considered. The influence of the original stress of the main cable will be more remarkable along with the increase of suspension bridge span. The stiffening girder is more flexible, and the corresponding flexural rigidity is less than axial rigidity of the main cable with the increase of span. In modelling, the link element of cable is endowed with original strain to make the main cable to be prestress system, which can bear load. The original prestress consolidated in structure derives the corresponding stress matrix, thus reflecting nonlinear influence of cable sag effect. The nonlinear influence of structure is achieved by opening the large deformation button of Newton-Raphson option.

4 Backward analysis

In backward analysis, structure analysis is conducted according to reserve process of bridge construction to get ideal location and mechanism behaviour of components such as cable, etc. The above results are compared with forward analysis for construction direction. Starting from the given completion state, backward analysis derives the main construction condition, thus ensuring that the constructed bridge meets the design requirements. Multi-power self-anchored suspension bridge is conducted with backward analysis by removing the second dead loads such as bridge deck pavement and sustaining the girder, or even removing the girder and sling to return to free cable state. Taking the completion state as the origin, backward analysis aims at discussing cable shape and mechanism behaviours of the main girder and tower in first dead load and free cable states.

4.1 ANALYSIS OF COMPLETION STAGE

After setting up Finite element completion model, the main cable and suspender, endowed with certain original stress, are substituted in ANSYS for calculation, adjustment and recalculation. The iterative calculations derive the following results:

Displacement change is stable around the first trial calculation value: Figure 5 shows that bridge displacement is about 0.1054m; Figure 6 shows that vertical displacement of main cable about -0.0898m.

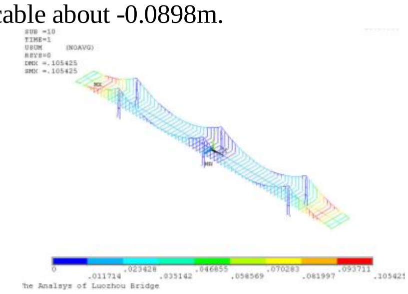

FIGURE 5 Bridge Displacement in the Completion Stage

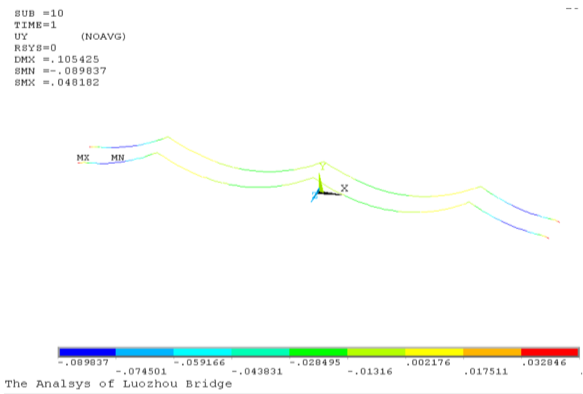

FIGURE 6 Vertical Displacement of Main Cable

In completion state, unbalanced force of the main cable at the top of the main tower is zero, reflected in small shear force, bending moment and large vertical axis pressure of the main tower. Table 2 shows the internal force value of key section.

Then the initial strain value of the final cable is calculated and substituted in ANSYS to get a rational finite element completion model. The mechanical characteristics of the completion state are as follows.

TABLE 2 Mechanical Characteristics of Main Tower

Section Position		Bending Moment (kN•m)	Shear Force (kN)	Axial Force (kN)
Section of Bottom Tower	Middle Tower	1051	1069	-24533
	Side Tower	898	1123	-25113
Section of Bottom Crossbeam	Middle Tower	1449	333	-18414
	Side Tower	1707	364	-18995
Section of Middle Crossbeam	Middle Tower	425	166	-14820
	Side Tower	439	169	-15002

In finite element model, the maximum of bridge displacement is 0.1054, which is distributed in side spans near anchorage zone. The main span has a displacement of about 0.0235m, with even distribution. The maximum of vertical displacement is 0.0899m, distributed in the side spans of the main cable and girder near anchorage zone. In multi-power self-anchored suspension bridge, the main cable anchored in the girder end produces large axial tension. Thereinto, the horizontal component is the prestress of girder for free and the vertical component has a bad influence on the girder of anchorage end: the girder end is lifted by 0.5604m; the girder produces angle displacement by winding side piers; the girder of side spans deflected with the largest vertical displacement of 0.0899m and the axial compression deformation of 0.0321m; the vertical displacement of the main tower which bears axial pressure is 3mm.

Multi-power self-anchored suspension bridge, as a complicated combination, has components with different characteristics. Among them, the main cable has the largest linear change while the main tower has the smallest deformation. The girder has the largest bending moment at the anchor end abutment of side spans (See Figure 7) because the cantilever end of anchor segment needs to bear huge initial tension caused by the main cable.

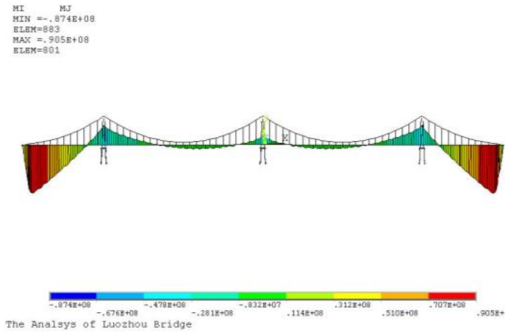

FIGURE 7 Moment of Main Girder in the Completion Stage

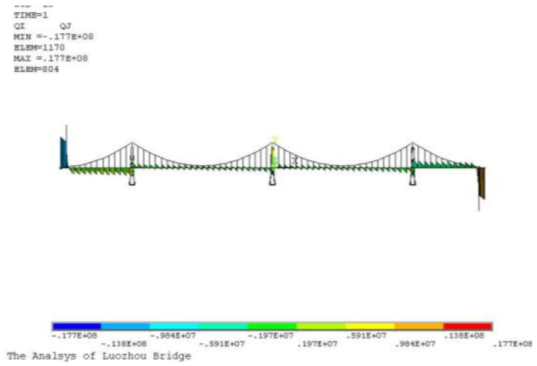

FIGURE 8 Shear Force of Main Girder in the Completion Stage

The saddle weight put in the abutment section results in large shear force and positive bending moment on side pier section (See Figure 8). This position should be conducted with local force analysis and strengthened.

4.2 ANALYSIS OF DEAD LOAD STAGE

The model at completion stage derives the model under first dead load by removing the second dead load. At the first dead load stage, the whole girders are separated from the temporary piers. The calculation shows that the largest displacement of the whole bridge is not near the anchor end of the main span but in the middle of the main span (See Figure 9), with a value of 0.2703m. Figure 10 shows that the largest vertical displacement of the main cable is 0.2698m. The largest displacement of the girder is 0.2702m, which is slightly larger than that of the main cable. The displacement of side span, less than 0.0700m, is smaller than that of main span, thus reflecting that action effect of main span to load is more obvious than side span.

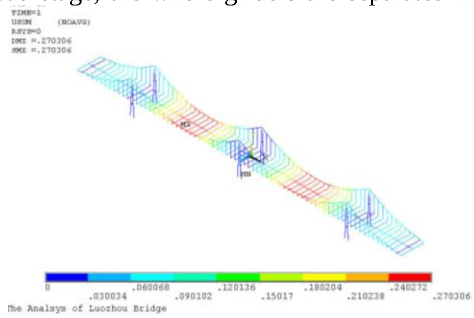

FIGURE 9 Bridge Displacement Under First Dead Load

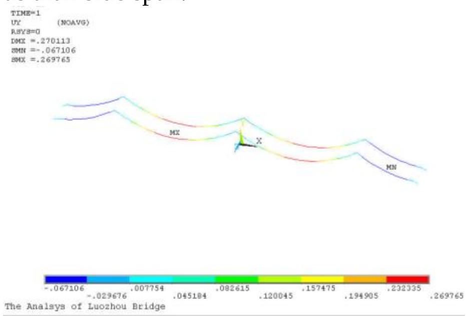

FIGURE 10 Displacement of Main Cable Under First Dead Load

The bending moment of main girder at the completion stage has large difference with that under first dead load (See Figure 11). Bending moment presents positive in main girder of both sides of the main tower and negative in middle span. In middle tower, it reaches the largest value. Figure 12 shows that the largest shear force location changes obviously. Compared with the completion stage, the external load decreases after removing the second dead load, and the location of dangerous section also changes, although the largest bending moment decreases little. So, the dangerous degree of self-anchored suspension bridge is determined by complicated linear change and redistribution of internal force of structure system instead of external load.

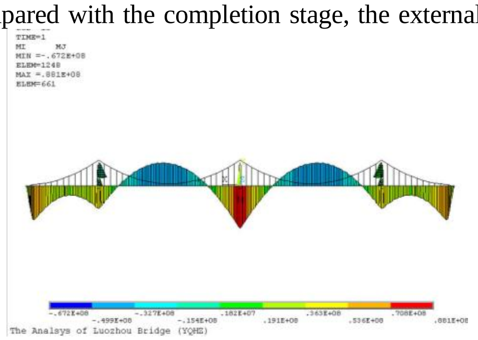

FIGURE 11 Moment of Girder Under First Dead Load

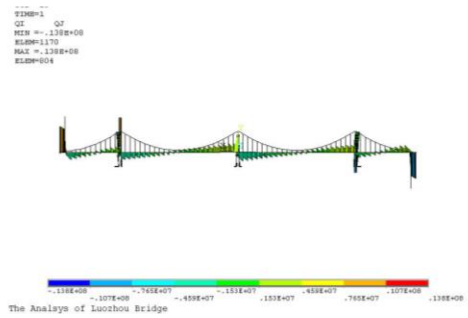

FIGURE 12 Shear Force of Girder Under First Dead Load

4.3 CABLE FINISH STAGE

In ANSYS model, the girder under first dead load is conducted with false work, and the suspender connecting to the main cable is removed to achieve the model in cable finish stage. It is realized by deleting link element of suspender and restraining the girder in terms of the design drawing. The construction process is usually simulated by element birth and death.

However, it is not suitable for geometric nonlinear self-anchored suspender bridge because element birth and death in ANSYS is not element addition or deletion. The dead element of structure construction is simulated by multiplying the element rigidity matrix by a small coefficient in ANSYS. The link elements of main cable and suspender are endowed with certain initial strain, and their attributes are not affected by birth and death element options in modelling [5]. So, it is not suitable to use birth and death element analysis. The calculation shows that the main cable deformation is large in middle span, and small in other positions.

The stiffening girder supported by temporary piers has a simple mechanical characteristic at cable finish stage. The largest displacement of the whole bridge is 0.9474m, which is reflected in vertical deformation of the main cable. Actually, research on cable finish stage is to determine pre-bias of the cable saddle. The main cable at the cable saddle of side tower is shifted by 0.2402m towards the middle tower direction, so the cable saddle of side tower should be conducted with equivalent pre-migration towards the opposite direction (side span direction).

4.4 MAIN CABLE CURVE

The main cable is the main bearing member, and its linear change affects construction of the whole bridge. Overall, the vertical displacements of the three stages are different (See Figure 13). Therefore, in backward analysis, the displacement of main cable changes a lot at different stages. Especially, the displacement change of main cable in the middle of main span is the largest, with a difference of 1m (from cable finish to completion stage). Figure 13 reflects large geometric nonlinear deformation of the main cable in construction of multi-power self-anchored suspension bridge.

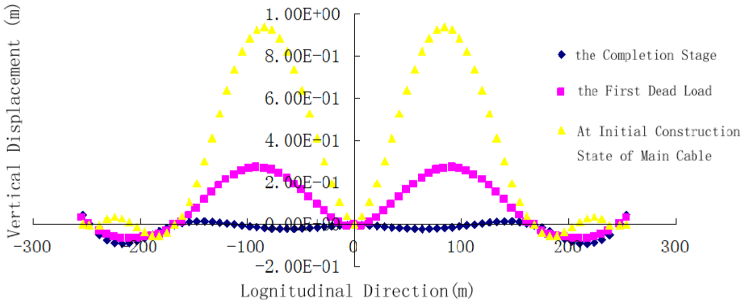

FIGURE 13 Displacement of Main Cable at Different Stages of Initial Construction State

The shape at cable finish stage got by backward analysis has certain difference because of nonlinear influence of multi-power self-anchored suspension bridge. Starting from the above shape, the shape at completion stage is calculated using forward analysis. If the difference is too large, then the initial shape at cable finish stage will be readjusted until the shape difference at completion stage meets the requirement. Consequently, backward analysis, as the method to check key procedure, cannot be the direct method for construction control.

5 Forward analysis

5.1 BASIC THOUGHT

Forward analysis is a common method to simulate construction process of multi-tower self-anchored suspension bridge. Simulation of construction process derives displacement change and mechanism behaviour of structure, thus providing assurance for construction control. So, forward analysis is a main method to analysis parameters such as geometric nonlinear influence factors and temperature change of self-anchored suspension bridge.

Forward analysis is to determine linear change of the main cable for multi-tower self-anchored suspension bridge based on the principle of constant component length without stress and balanced load. Firstly, the corresponding cable finish stage is determined by certain design data such as arrangement of bridge span, rise span ratio of main cable, main-side span ratio and design elevation of the main tower and girder, as well as assumed pre-bias of cable saddle and clamp. Secondly, the factors such as main tower offset, saddle push, temporary abutment separation, saddle point of tangency of main cable, etc. are considered. Construction process like cable tension is simulated to achieve the main cable and girder lines at bridge completion stage. The above results are compared with the design values of completion stage. If the results do not meet the requirement of accuracy, then the assumed variable will be corrected and finite element iterations repeated until the accuracy is satisfied. At last, the unstressed lengths of main cable and suspender as well as design and construction parameters such as pre-bias of cable saddle and clamp. The above process is determined by the initial state, load state and target state [6-7]. Thereinto, the target state is the rational completion stage of design; the initial state is the initial construction stage; the load state is realized by bridge system transformation after suspender tension and bridge deck pavement. The essential of forward analysis is to compare target state with load state. If the difference is too large, then correct the initial state until the difference meets the accuracy. The process to get the load state can be exported to be the ideal state in construction.

5.2 CABLE FINISH STAGE

The initial work of cable construction based on self-anchored suspension bridge is to determine the cable finish stage and set up baseline cable. The linear accuracy determines cable tension and main cable linear control at later stage. Free cable coordinates got by backward analysis is used to set up finite element model at cable finish stage. The main cable line of completion stage has certain difference with that of design stage. So, the difference should be controlled within an allowable range by correcting parameters including initial strain of main cable and pre-bias of cable saddle, and rebuilding a rational model at cable finish stage. According to principle of constant length without stress and balanced force, the initial cable finish line meeting the construction requirements is achieved by main cable line design at completion stage. The finite element model at cable finish stage is built in terms of free cable line, girder elevation, pre-bias of saddle, etc. Thereinto, spring element is used to simulate pre-bias of saddle, namely, spring element with certain rigidity is endowed with a couple of balanced forces. The forces, with the same value and different directions, are adjusted to achieve the push procedure.

5.3 SUSPENDER TENSIONING

In construction of multi-tower self-anchored suspension bridge, rational tensioning sequence and force are used to determine suspender tension method. So, the above method can avoid increase of project time as well as large stress and strain of partial cable caused by excessive tensioning force, which can result in project accident. The ideal construction of suspender tension in batches, namely the ideal suspender force in periods, is analysed. Meanwhile, suspender tensioning sequence is important. One hand, the suspender is symmetrically tensioned towards the anchor ends starting from mid-span. Because of different main-side spans, the suspender is tensioned from the anchor ends, 1/4 and 3/4 mid-span of main span and mid-span of side span to prevent excessive tower deviation after tensioning to a certain step. Other hand, the suspender is symmetrically tensioned towards both ends starting from the main tower. Different tensioning sequences, with different characteristics, follow principle of symmetry, thus avoiding unbalanced horizontal forces of main cable at the main saddle and large deviation of bridge tower. According to actual situation, rational suspender tensioning schedule should be found considering different suspender tensioning forces and sequences. In addition, the corresponding parameters in tensioning process are studied to get some rules for construction.

5.3.1 DEAD LOAD STAGE

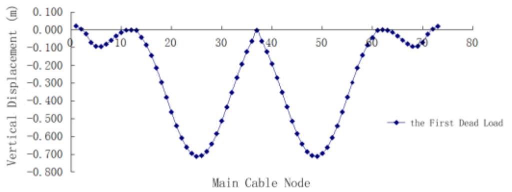

FIGURE 14 Vertical Displacement of Main Cable Under First Dead Load by Forward Analysis

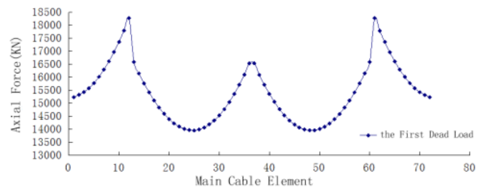

FIGURE 15 Axial Force Curve of Main Cable Under First Dead Load by Forward Analysis

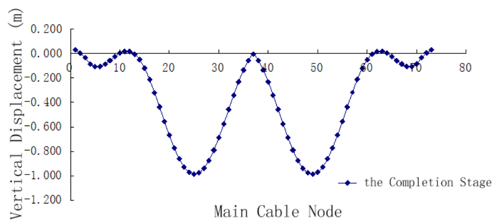

FIGURE 16 Vertical Displacement Curve of Main Cable in the Completion Stage by Forward Analysis

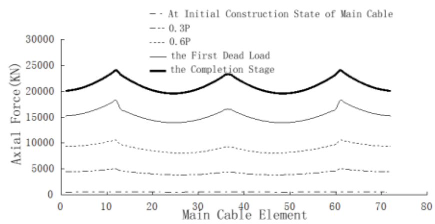

FIGURE 17 Axial Force Curve of Main Cable at different stages by Forward Analysis

In construction, when suspender tensioning force reaches certain designed value, stiffening girder will be supported by suspenders (slings) instead of temporary piers (First dead load stage), thus realizing system transformation. The suspender tensioning is finished. At the same time, stiffening girder in mid-span of main span presents inverted arch, with the largest vertical displacement of 0.410m. Because of vertical component force of main cable at anchor ends, the largest vertical displacements of anchor ends of side span upwarping and mid-span downwarping are 0.022 and 0.047m, respectively.

In this situation, the main cables of the whole bridge have downward displacements: mid-span of main span has a largest vertical displacement of 0.712m; mid-span of side span 0.094m. Figure 14 shows that the main cable has a larger vertical displacement at mid-span and smaller at both sides, symmetrically changing around the tower axis.

Each axial force of the main cable is between 13957 and 18280kN (See Figure 15), and the whole unbalanced force at both sides of the tower is about 1693kN. So, unbalanced force at the top of bridge tower should be released in construction, thus moving cable saddle to designed completion position and pushing it to mid-span by 88.3mm. Besides, the main cable at both sides of saddle has small unbalanced force, with suspender forces between 724 and 871kN.

5.3.2 BRIDGE COMPLETION STAGE

In self-anchored suspension bridge, the weights are removed based on first dead load, and the second dead loads such as deck and facility are installed to achieve completion stage. In completion stage, linear changes of the main girder and cable are basically identical with those in first dead load stage. In construction, suspender should be slightly adjusted to make the target line close to design line. The deformation of the main span and girder is less than that in first load stage because the deck falls back by adding second load. Besides, the increase of vertical component force of the main cable at anchor end results in increase of side span downwarp. So, the dangerous degree of multi-tower self-anchored suspension bridge is determined by composition and acting position of the load instead of magnitude of load.

Figure 16 shows that the deformation of main cable in the completion stage, with more downwarp at mid-span, is identical with that in first dead load stage. The largest vertical displacements of main and side spans are 0.989 and 0.106m, respectively. So, the second dead load has little influence on the main cable line. At the same time, each axial force of the main cable is between 19606 and 24089kN; axial forces at both sides of mid-tower are equal; unbalanced force at both sides of side tower is 838kN. Therefore, saddle should be pushed by 50.5mm to the design position, and suspension force is between 1048 and 1114kN in second dead load stage.

5.4 PHASE-BASED STATE

In forward analysis, linear change of main cable and girder, as well as mechanical behaviour of main cable at each stage are compared to achieve the following change regulation: if the suspender forces are 0.3P and 0.6P, the whole girders except navigation span will have little displacements because they are not completely separated from temporary piers; if suspender force is large enough to support first dead load including dead weight of the main girders, the main girders will have largest change of displacement in the middle of side and main spans; if the second dead load is added, the displacement of main girder at mid-span will overall drop along with the increase of the load, with the largest drop of 0.37m. Meanwhile, the middle of side span will drop to 0.057m and anchor end will rise to 0.035m.

In forward analysis, the linear change of the main cable is identical. Without considering suspender tensioning sequence, the suspender forces, changing from 0.3P and 0.6P to the values at first load and completion stages, are gradually added to the main cable. Figure 16 shows that the displacement of mid-span of main cable gradually increases, and the largest downwarping at the completion stage reaches 0.989m.

Figure 17 shows that each axial force of main cable is about 500kN at cable finish stage, and axial force caused by dead weight of main cable approximates a straight line. If the suspender force reaches 0.3P, the whole axial forces of the main cable will be increased by a level. Especially, axial force at bridge tower will be 5000kN, thus indicating that unbalanced horizontal force occurs at both sides of saddle. If the suspender force reaches 0.6P, the axial force of main cable will rise to 10000kN more or less and unbalanced force at the top of side tower will continue rising. At the first dead load stage, axial force of main cable valuing from 13957 to 18280kN will present geometry to achieve the largest unbalanced force at the top of side tower. The unbalanced force can be released by pushing pre-bias saddle. At the bridge completion stage, axial force of main cable rises to 19606~24089kN; however, the unbalanced force at both sides of saddle is released. Analysis shows that axial forces of main cable at both sides of top of mid-tower are approximately equal, and top of mid-tower short of vertical restrains has no or little unbalanced force.

6 Conclusions

A finite element three-dimension space model is built by ANSYS based on Luozhou Bridge – the first multi-tower self-anchored suspension bridge in China. After that, the work aims at developing finite element analysis using backward and forward methods and comparing closing accuracies and characteristics of lines calculated by the two methods. Backward analysis is only a method to check key construction procedure. The analysis shows that the largest bending moment of main girder is at the anchorage bearing of side span, and the anchor end of cable has special mechanical behaviour. In construction of triple-tower self-anchored suspension bridge, the main cable presents geometric nonlinear characteristics. Then, the work analyses linear change law of the main cable in different load conditions, and discusses unbalanced forces of side and main towers to achieve an effective method (pre-bias saddle) to release them. Therefore, the work provides key force analysis for multi-tower self-anchored suspension bridge, making a good example for design and construction of similar bridges.

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