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Cable Forces Optimization Loading and Test Result in the Model Test for the Pylon of the Joint-pylon Cable-stayed Bridge with Four Cable Planes and Twin Separate Girders

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Abstract:

One of the schemes of Yongjiang super-large bridge is a cable-stayed bridge with four cable planes, united twin-pylons and twin separate prestress concrete girders. The joint part of twin-united pylons is under combined torsion, flexure and shear. The force state in separate twin bridges is in coupling conditions. In order to assuring the safety and credibility of the united twin-pylons, the test for the whole pylon is made with a scale-down model of 3: 40. The most critical conditions of the pylon are simulated by tensioning cables. In order to tension the least cables, mathematical programming models and numerical programs for the least cables are created. The equivalent cable forces and the tension forces under different load levels are determined. The optimization cable forces and test cable forces are compared and analyzed. The result shows that the optimization method is feasible and the interaction of cable forces between united twin-pylons is less.

Keywords: *Bridge engineering, Cable-stayed bridge, Model test, Joint-pylon, Cable force optimization.*

I. INTRODUCTION

One of the schemes of Yongjiang super-large bridge is a cable-stayed bridge with four cable planes, united twin-pylons and twin separate prestress concrete girders. The bridge's span is 63+132+468+132+63m (Fig 1), which is the first long span in the joint-pylon cable-stayed bridge spans. The cable-pylon's shape is diamond-type, with total hight-144.069m. The upper pylon columns are joined with concrete slab at the top region. Two main pylons are joined at the region nearby the cross beam (Fig 2). At the middle span and side span, 28 pairs of stayed

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cables are set on each pylon column. The cable of number 0 is vertically set on the pylon. 456 cables are set in the whole bridge. The basic distance of cables on the girders is 8m, which belongs to dense cables.

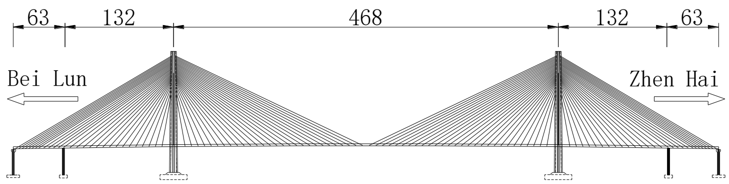

Fig 1: Elevation drawing of Yongjiang super-large bridge /m

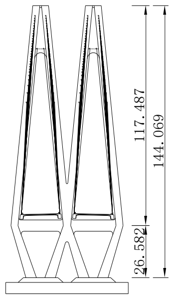

Fig 2: Elevation drawing of the bridge pylon/m

The mechanic behavior of joint-pylon is complex. In the twin bridges, the twin girders are separate and the main pylons are joined. The force state in twin bridges is in coupling conditions. Under the non-uniform longitudinal load and the asymmetric vertical or lateral load, the joint part of twin-united pylons is under combined torsion, flexure and shear. This structure is rare. No precedent can be referenced. In order to study on the mechanic behavior of this structure, the model test for the pylon is done. Due to the limited space, only the cable forces optimization, cable forces loading and test results for the test are mainly introduced in the paper.

II. BRIEF INTRODUCTION TO THE DESIGN OF TEST MODEL

Based on the scale of the test field, the test model is done with a scale-down model of 3: 40, with hight-11.443m, length-37.762m and width-5.250m (Fig 3, Fig 4). The model is designed according to the principle of stress equivalent and is made using the same material as the real structure [1-3]. The geometry size of the model pylon is designed strictly observing the similarity ratio of 3: 40. The stayed cables are set following to the principle which must ensure that the stress of the model pylon is equivalent with the real pylon. The cables in the model can't be completely set according to the number in the real structure because the spatial scale in the model is relatively small. 28 pairs of cable-stayed on each pylon column in the real pylon are reduced to 9 pairs in the model pylon. 72 cables are drafted in the model. Every cable's type is 7Φ5. The cable of number 0 is simulated by counter balance. As shown in Fig 3, cables at the

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model's left are numbered row 1 - 9, cables at the model's right are numbered row 11-1 9. As shown in Fig 4, cables of each row has four planes numbered A, B, C and D.

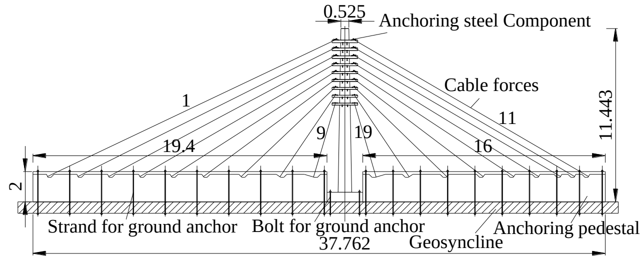

Fig 3: Elevation drawing of the model /m

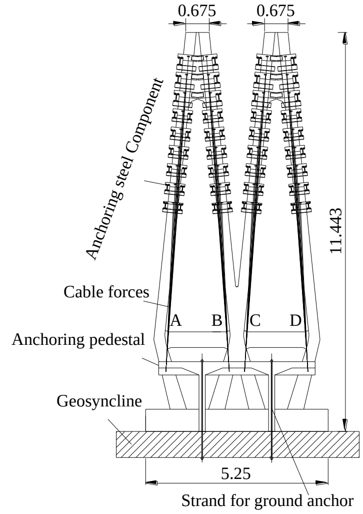

Fig 4: Side view of the model /m

The most critical cases of the real pylon must be simulated in the model test. In the real structure, factors leading to the most critical cases are a lot, such as self weight, temperature, wind load, live Load and so on. Some factors don't act on the pylon directly or the action mode is complex. It is very difficult to simulate the factors directly, so, the stayed cables are tensioned to reach the pylon's stress states which are produced by the factors.

III. CABLE FORCES OPTIMIZATION LOADING

3.1 Loading Case

Some control sections can be selected through calculation analysis. According to the stress states of the control sections under all cases, three Loading cases are selected to be simulated in the test. Case I: Counter balance load. Case II: Combination of dead load and longitudinal wind. Case III: The state with the maximum dislocation of the top of pylon along the bridge's longitudinal direction. Case II and case III are simulated by tensioning cables on the basis of case I. In order to tension simply and waste the least resources, on the basis of meeting the requirement to ensure that the stress of the model pylon is equivalent with the real pylon, the

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least cables should be selected to be tensioned from 72 cables which are the original drafted values.

3.2 Optimization Model

The objective of cable forces equivalence is to determine a group of cable forces which can ensure that the stress of the model pylon is equivalent with the real pylon under corresponding cases. The number of control parameters is usually not equal to the number of design parameters, and cable forces have limit values, so it is impossible to obtain cable forces by establishing and solving a equation directly, thereupon, the nonlinear programming model shown in equation (1) is established. Optimization cable forces can be obtained by solving iteratively the programming equation (1).

$$\left.\begin{aligned} &Min \quad \phi(\boldsymbol{T}) = \alpha_1 \frac{\left\| \boldsymbol{f}_M - \boldsymbol{f}_{gM} - \boldsymbol{M}(\boldsymbol{T}) \right\|}{\left\| \boldsymbol{f}_M - \boldsymbol{f}_{gM} \right\|} + \alpha_2 \frac{\left\| \boldsymbol{f}_N - \boldsymbol{f}_{gN} - \boldsymbol{N}(\boldsymbol{T}) \right\|}{\left\| \boldsymbol{f}_N - \boldsymbol{f}_{gN} \right\|} \\ &\qquad \boldsymbol{T} \subseteq [\, T_1, T_2, T_i, \ldots, T_n] \\ &S.T. \quad T_i(200 - T_i) \geq 0 \end{aligned}\right\} \tag{1}$$

$$\boldsymbol{M}(\boldsymbol{T}) = \begin{bmatrix} RM_{11} & RM_{12} & \cdots & RM_{1n} \\ RM_{21} & RM_{22} & \cdots & RM_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ RM_{m1} & RM_{m2} & \cdots & RM_{mn} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ \cdots \\ T_n \end{bmatrix} \quad \boldsymbol{N}(\boldsymbol{T}) = \begin{bmatrix} RN_{11} & RN_{12} & \cdots & RN_{1n} \\ RN_{21} & RN_{22} & \cdots & RN_{2n} \\ \cdots\cdots & \cdots\cdots & \cdots & \cdots\cdots \\ RN_{m1} & RN_{m2} & \cdots & RN_{mn} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ \cdots \\ T_n \end{bmatrix}$$

Where m and n are the total number of control sections and cables respectively. α_1 and α_2 are the weight coefficients of moment and axial force respectively. $\boldsymbol{f}_M$ and $\boldsymbol{f}_N$ are the total moment and total axial force of control sections under corresponding cases in the model pylon respectively, which are the target forces of control sections in the model pylon, which can be transferred from forces of corresponding sections in the real pylon by coefficients of forces similarity ratio [4-6]**.** $\boldsymbol{f}_{gM}$ and $\boldsymbol{f}_{gN}$ are the moment and axial force of control sections under dead load and counter balance load in the model pylon respectively. $\boldsymbol{M}(\boldsymbol{T})$ and $\boldsymbol{N}(\boldsymbol{T})$ are the moment and axial force of control sections under cable forces in the model pylon respectively. RM_{ij} and RN_{ij} are the moment and axial force of control section numbered i under unit cable forces of the cable numbered j in the model pylon respectively.

The constrained nonlinear programming model equation (1) can be transformed into unconstrained nonlinear programming model equation (2). The method of DFP shown in Fig 5 can be used to solve iteratively the equation (2) [7]. Cable forces equivalence for the least cables can be considered to obtain a group of cable forces which must be the solution of programming model equation (2) and must meet the requirement of equation (3) on the basis of tensioning the least cables. The equivalent cable forces can be solved by the optimization flow shown in Fig 6.

$$Min \quad f(\boldsymbol{T}) = \phi(\boldsymbol{T}) + \sum_{i=1}^{n} B(T_i) \tag{2}$$

Where the function $B(T_i)$ is the exterior penalty function of design variables.

$$\max_{i=1,2,\dots,m}\left|1-\frac{M_i(T)}{f_{Mi}-f_{gMi}}\right|\le\varepsilon_1,\ \max_{i=1,2,\dots,m}\left|1-\frac{N_i(T)}{f_{Ni}-f_{gNi}}\right|\le\varepsilon_2 \tag{3}$$

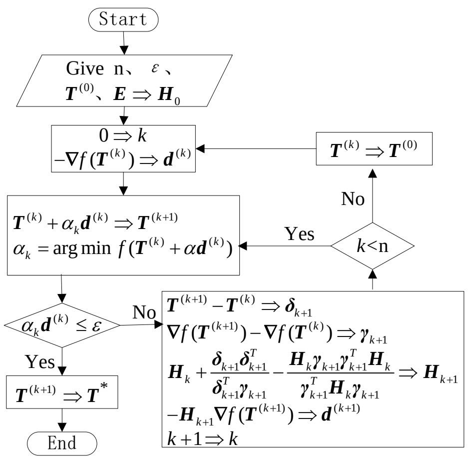

Fig 5: Flow diagram for the method of DFP

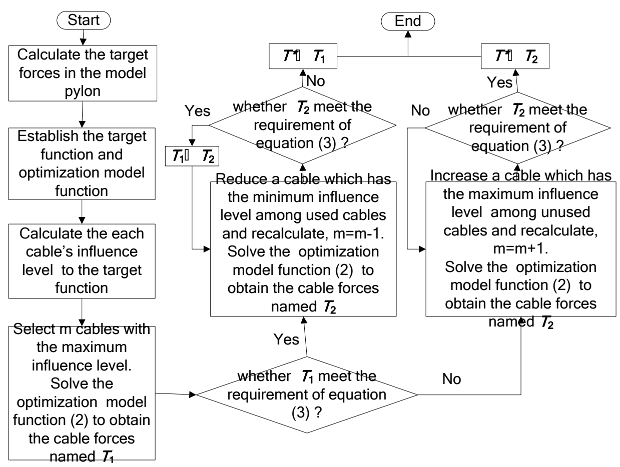

Fig 6: Flow block diagram of optimization of cable forces for the least cables

According to the above principle, 32 cables can be finally selected to be tensioned in the test, final cable forces namely target forces of the cables can be calculated simultaneously. In order to meet test requirements and ensure security of the structure, the cables are tensioned by the method of multi-level loading before cable forces reaching the final values namely target forces. Cable forces at each load level is respectively 10%, 20%, 40%, 60%, 80%, 100% of the final forces. 32 cables are tensioned successively by the sequence: 9-B, 19-B, 9-C, 19-C, 9-A, 19-A, 9-D, 19-D, 3-B, 13-B, 3-C, 13-C, 3-A, 13-A, 3-D, 13-D, 2-B, 12-B, 2-C, 12-C, 2-A, 12-A, 2-D, 12-D, 1-B, 11-B, 1-C, 11-C, 1-A, 11-A, 1-D, 11D. The cables' number can be shown in Fig 3 and Fig 4. Likewise, tension forces under different load levels can be determined by the method of influence matrix and programming solution.

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IV. ANALYSIS OF TEST AND CALCULATED RESULTS

4.1 Test Values and Calculated Values

Stress levels of the model structure are in reasonable limit values in the processes of tensioning stayed cables. Due to the limited space, only test cable forces and calculated cable forces under case II are list out (Fig 7). The error interference is relatively significant because the absolute values of cable forces are relatively small at the previous two lower load levels under case II, so the relative difference values of test cable forces and calculated cable forces are relatively large, the maximum relative difference value is about 15%, but the maximum relative difference value is less than 5% at other load levels under case II. It is shown that test cable forces are basically same as calculated cable forces, so the optimization method is feasible and the tension processes in the test are reasonable.

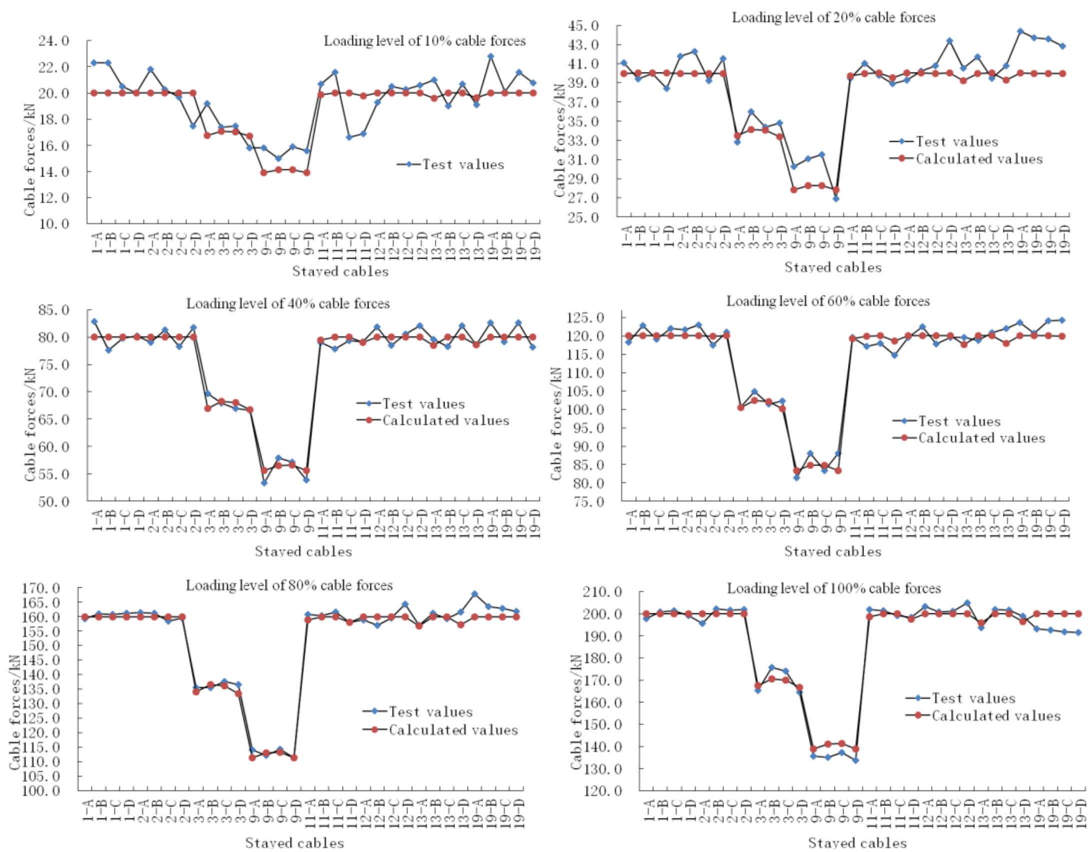

Fig 7: Calculated cable forces and test cable forces at each load level under case II

4.2 Interaction of Cable Forces

The test results show that most of active tensioning force of one cable is allocated to the cable itself and the tensioning force of one cable has limited effects on another one. The same conclusion can be obtained by analyzing the influence matrix of tensioning force, Fig 8 indicates that variation conditions of cable forces at the 80% load level under case II when the cable namely 1-A, or 1-B, or 1-C, or 1-D is tensioned. The bar graphs show that the cable force of the cable which is being tensioned has a great variation, the forces of the other cables has less variation, and particularly, the forces of cables on one pylon has significantly less variation when a cable on another pylon is tensioned. It can be concluded that integral rigidity of the structure and rigidity of the joint part of twin-united pylons are enough large, twin-united pylons can be regarded as mutually independent pylons to a certain extent.

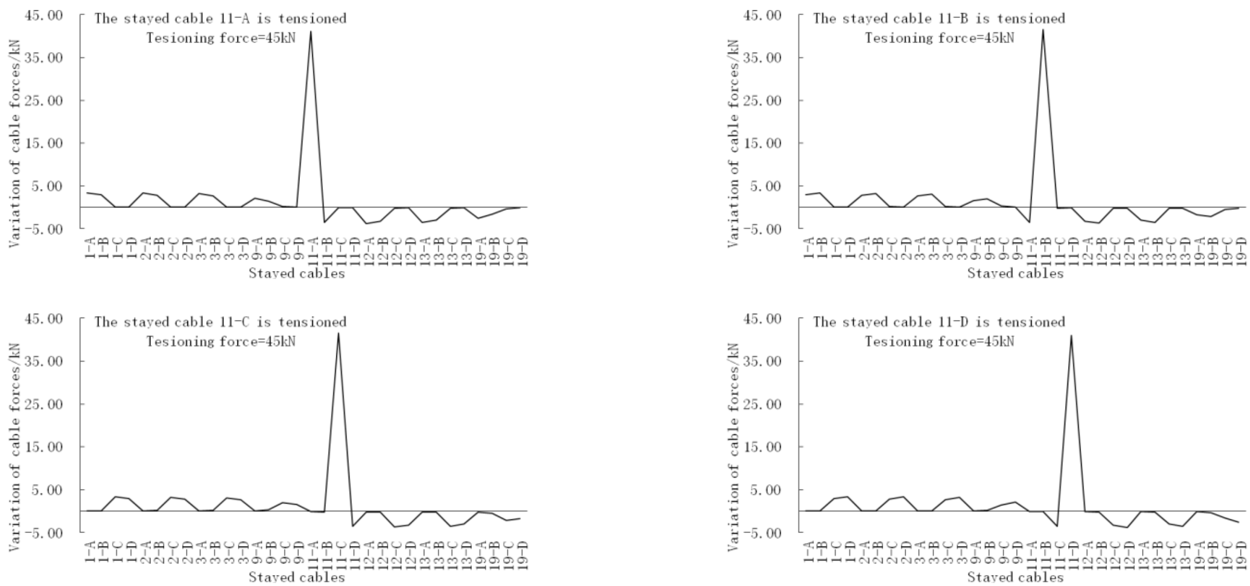

Fig 8: Variation of all cable forces when some cables are tensioned at the 100% load level under case II

V. CONCLUSIONS

It is a major characteristic that loading cases are simulated by tensioning stayed cables in the model test. In order to avoid simulating directly the factors which lead to the stress states of the structure, the stayed cables are tensioned to simulate the pylon's stress states which are produced by the factors. Mathematical programming models and numerical programs for the least cables are created. The equivalent cable forces and the tension forces under different load levels are determined. In the test, the stress states of the structure are simulated by tensioning the least cables. At the previous two lower load levels, the test errors are relatively larger due to the small absolute values of cable forces, but it does not influence the final test load which is our concern. The test loads are in controllable range. With the increase of cable forces, the relative errors of test cable forces gradually become smaller. The final relative errors are controlled at 5%. The optimization cable forces and test cable forces are compared and analyzed. The result shows that the optimization method is feasible and the tension processes in the test are reasonable. By studying on the analysis for the interaction degree of cable forces, it is shown that the reciprocal distribution of cable forces is less, and particularly, the interaction of cable forces between united twin-pylons is significantly less. The results indicate that integral rigidity of the structure and rigidity of the joint part of twin-united pylons are enough large.

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