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Ultimate Load Capacity of the Cable Tower of Liede Bridge

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***Abstract*—**The cable tower of Liede Bridge is a double-column curved-lever arched-beam portal framed structure. Being novel and unique in structure, its cable tower differs in complexity from traditional ones. This paper analyzes the ultimate load capacity of cable tower by adopting the finite element calculations and model tests which indicate that constitutive relations applied here give a better simulation of actual failure process of prestressed reinforced concrete. In vertical load, horizontal load and overloading tests, the stepped loading of the tower model is of linear relationship, and the test data has good repeatability. All suggests that the cable tower has good bearing capacity, rational design and high emergency capacity.

***Keywords*—**Cable tower of Liede Bridge, ultimate load capacity, model test, nonlinear finite element method

I. INTRODUCTION

IN recent years, self-anchored suspension bridge is more favorably and competitively proposed than other short and medium span bridges [1,2], because mass anchor is not required, there are fewer restrictions from terrain and it is more flexible in setting linear space, and the construction cost is lower. Thus, it can be built into twin-tower three-span suspension bridge or single-tower double-span suspension bridge. The self-anchored suspension bridges which have been completed in China include Pingsheng Bridge, Sanchaji Bridge, Wanxin Bridge, Jiangdong Bridge, Liede Bridge, Nanjijiang Xinzhou Bridge, etc, and some are still under planning, designing and construction [3, 4]. Cable tower of self-anchored suspension bridge is an important part for transmitting super-structural load. Analysis and study of the stress state, transfer mechanism and stress concentration through the model tests and finite element calculations are very significant for the design of the main tower of self-anchored suspension bridges.

Lied Bridge belongs to self-anchored suspension bridge of single-tower double-span structure. Its main hole uses the combined spans of 167m+219m, and its stiffened girder is 47m+167m+219m+47m four-span continuous girder, as shown in Figure 1. The main tower of Liede Bridge, 128m high, is the most eye-catching part for its novelty in appearance, which appears like two interlocked conchoidal curved shells, making it difficult for construction. The inner and outer contours are made up by ellipses with an open top. The transverse section of its single-column pylon is trapezoidal-like with an overall width of 8.2m to 20.6m in cross section and 2m in lateral section. The cross section of its pylon is of single-cell single-box prestressed concrete structure, 1m to 2m in wall thickness. The cross beam of its top, as shown in Figure 2, is of two-cell single-box prestressed concrete structure, which is 10m high and 12.628 maximally wide.

The cable tower of Liede Bridge is of double-column curved-lever arched-beam portal framed structure, whose behaviors of stress are distinctly different from traditional portal framed structures [1, 2].

(1) The cable tower has a complex construction for using big curved surface composite structure, particularly in its cross beam. Affected by the main cable's space line shape, the top cross beam of the cable tower has to bear a direct concentrated load from the main saddle. For its stress transcends the lateral rigidity offered by regular cross beams, this cross beam becomes a force transmission component for the structure. The cable tower's inner construction is more complicated with its behaviors of stress unclear. Moreover, the rigid frame in nodal point between pylon and cross beam is larger-dimensioned, thus making the rigid region effect more evident than traditional frame structures. As the length selection of its rigid arm would impose great influence on the results, the force transmission in the beam-column point also appears quite unclear.

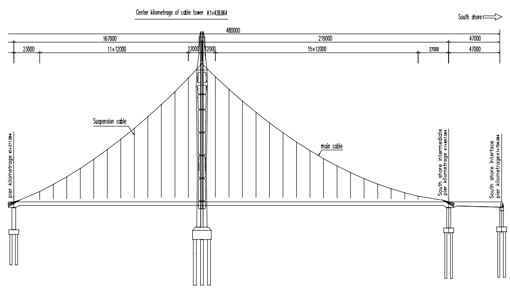

Fig. 1 General structure layout of the main bridge.

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(2) The cable tower of Liede Bridge has a quite complex characteristics of stress. A considerable additional bending movement is produced when an axial force is transmitted by the pylon. Its action line of force varies in curve along the pylon, which is characterized by compression curved member. Also, the column of the cable tower is a curved surface with a considerable wall thickness. Since there are great differences in the environmental temperature, the gradient of temperature in cross section of cable tower column has a considerable influence on structure stress.

Regarding this type of unique cable tower structure embracing several different complexities as stated above from traditional structures, its structural behavior is not quite clear. Hence, in order to ensure safety of cable tower and test the rationality in tower structure, it is necessary to give a detailed analysis of cable tower's ultimate bearing capacity by theoretical calculations and model tests.

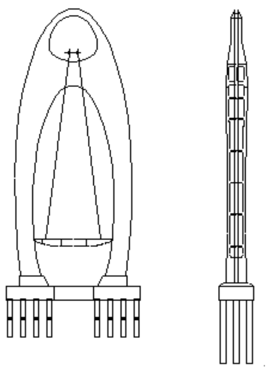

Fig. 2 Structure diagram of cable tower.

II. Analytical Methods For Ultimate Bearing Capacity

2.1 Analytical Model of Liede Bridge

A separate finite element model is built, with the concrete adopting SOLID65 element and the prestressed reinforcement adopting LINK8 element, whereas the bond-slip between the reinforcement and concrete is not considered. In this model, the loading point is uniformly loaded and the bearing support is plane constrained. As the model is huge with numerous elements (46977 elements in total and 14020 nodal points) and its material is of nonlinearity, the calculations involved are considerable. Therefore, it makes sense to build a rational finite element model to improve computational efficiency. As for symmetry of the tower's vertical central line of Liede Bridge, it is to be calculated in cis-1, 4-structure instead, so as to reduce relevant computations. Figure 3 and Figure 4 present the finite element model.

2.2 Material Constitutive Relation

In this paper, for better calculation convergence, the concrete uniaxial stress relation in its ascending stage uses the formula stipulated in "*The Chinese Code for Design of Concrete Structures* " (GB 50010-2002), while in its descent stage it is

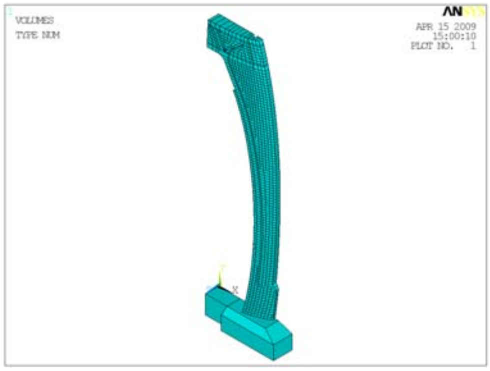

Fig. 3 Finite element mesh of the cable tower

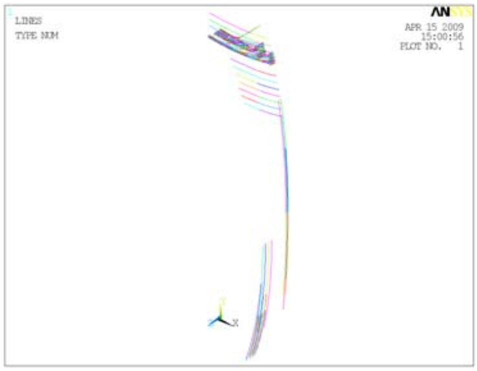

Fig. 4 Overall plan of prestressed reinforcement of tower

dealt with Hongnestad methods. That is:

When, $\varepsilon_c \le \varepsilon_0$,

$$\sigma_c = f_c\left[1-\left(1-\frac{\varepsilon_c}{\varepsilon_0}\right)^n\right] \tag{1}$$

And when, $\varepsilon_0 \le \varepsilon_c \le \varepsilon_u$,

$$\sigma = \sigma_0\left[1-0.15\left(\frac{\varepsilon-\varepsilon_0}{\varepsilon_u-\varepsilon_0}\right)\right] \tag{2}$$

Such results as $n=2$, $\varepsilon_0 = 0.002$, $\varepsilon_{cu} = 0.0033$ can be gained respectively in terms of specifications and regulations. The above curve adopts a series of point fitting input, and uses MISO simulation, as shown in Fig.5.

The stress-strain relation of prestressed reinforcement follows the ideal elasto-plastic model without considering the reinforced stress intensification effect. Its expression is:

$$\left.\begin{aligned} \sigma &= E\varepsilon \quad (\varepsilon \le \varepsilon_y) \\ \sigma &= \sigma_y \quad (\varepsilon_y \le \varepsilon \le \varepsilon_u) \end{aligned}\right\} \tag{3}$$

where, E - Modulus of Elasticity , σ_y -Yield Stress; ε_y - Yield Strain, ε_u -Ultimate Strain (usually at 15 to 20 ε_y).

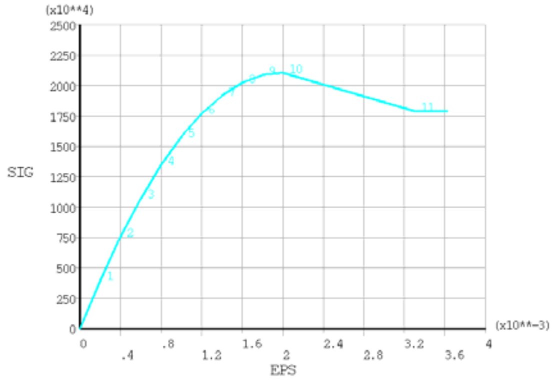

Fig. 5 Concrete Axial Compression Curve $\sigma - \varepsilon$

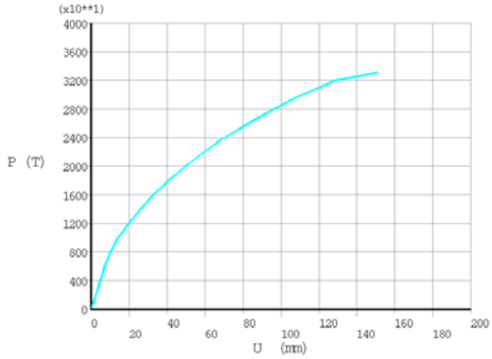

Fig. 6 Cross Beam Midspan Load-displacement Curve

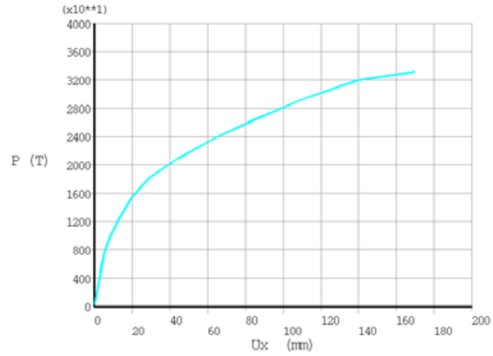

Fig. 7 Pylon Midspan Load-displacement Curve

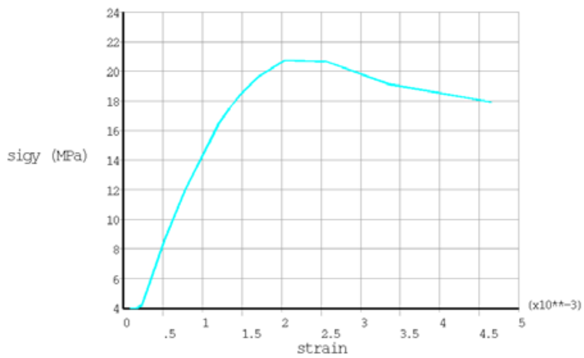

Fig. 8 Cross Beam Midspan Stress-strain Curve

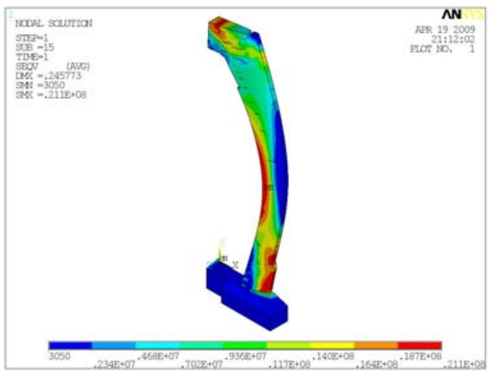

Fig. 9 Equivalent Stress Curve

2.3 Solution Method and Convergence Criterion

Newton-Raphson solution method is applied to carry out nonlinear finite element analysis of reinforced concrete structure. Both incremental-iterative method and displacement incremental method are effective, the latter is more applicable with a higher rate of convergence [8]. However, it is related to structural characteristics and step length. Prior to obtaining a solution every time, NR method would be used to estimate a residual vector, which is the balance between restoring force and the added load. After that, an unbalanced load method would be used to gain linear solutions and inspect astringency. If the results do not conform to convergence criterion, the unbalanced load will be re-estimated and the stiffness matrix will also be modified until a new solution comes out. This iteration will be continued unless convergence is achieved [9]. The loading regime is displacement loading regime while the convergence criterion is force convergence criterion [10, 11].

2.4 Analysis of Calculation Results for Ultimate Bearing Capacity of Cable Tower

Figure 6 and Figure 7 are the cross beam midspan load-displacement curve and pylon midspan load-displacement curve respectively. Figure 8 is the cross beam midspan stress-strain curve and Figure 9 is the equivalent stress curve. As shown in Figure 6 and Figure 7, the maximum load for cable tower is 331500KN. In case of F = 320000 kN, the compression strain of its cross beam top reads 0.003458 as shown in Figure 10, which is close to the concrete ultimate strain stipulated in "*The Chinese Code for Design of Concrete Structures*". Thus, from the above, a conclusion reached in this paper is that the ultimate load for cable tower of Liede Bridge is 320000KN (F=320000 kN), its design load is 75000KN and its safety factor is 4.27. As shown in Figure 8, the concrete stress-strain curve appears the same as that of concrete constitutive relation, which suggests reliable computational results.

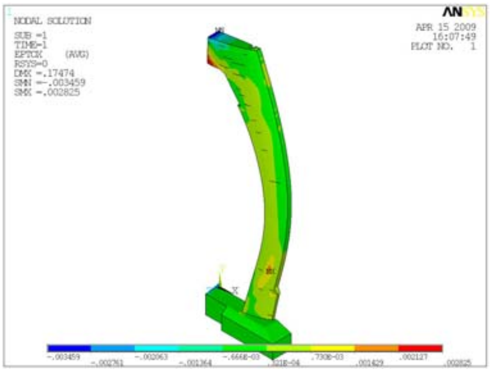

Fig. 10 K=32000kN tower concrete strain- ε_x

III. MODEL TEST

3.1 Model Design and Making of Cable Tower

1). Take the reduced scale of model length at 1⁄10 and that of stress at 1⁄10 in terms of similarity principle and similarity requirements of prototype for the model.

2). Materials used in model test for cable tower this time are the same as that in prototype. Particle-sized aggregate concrete is used to satisfy the compaction of vibration, and the consistency of modulus of elasticity of the materials must be initially ensured to meet likelihood ratio [5].

3). In the meantime, it is important to stimulate actual construction steps other than the cable tower's real structure. Placing concrete for the beam part of cable tower in accordance with the actual construction phases and setting the lateral bracing accordingly are the attempts for the model to rationally reflect real structure and dynamic mechanical behavior in each construction phase.

4). The same ratio of reinforcement in original section is used in reinforcement design of pylon and cross beam of this model, so as to make model stress and deformation similar to that in prototype [12].

5). The ratio of reinforcement used both in prestressed reinforcement of pylon and lateral prestress of base plate is the same as that in prototype. Restricted by the model's actual dimensions, prestress in base plate shall not use similar layout types to that of prototype, that is, level bending and vertical bending reinforcement. Hence, it shall adopt a layout type to guarantee equivalent bending moment in cross beam midspan [12,13], with its ratio of reinforcement equivalent to that of prototype.

3.2 Model-making of Cable Tower

The model making steps are as follows:

1). As the geology where the model is made is not ideal, concrete foundation is to be used with a bearing capacity of 250 KPa/m^2.

2). For the timber formwork of this model, the first step is to make molding beds for base, middle and top sections in each pouring phase according to the design drawing. Then timbers are used to connect each molding bed, after which the formwork is finished [3, 6].

3). With formwork completed, the next step is to place concrete in terms of construction procedures, in which the ratio of reinforcement in both reinforcement and prestressed reinforcement is the same as that of the prototype. Meanwhile, lateral bracing is installed when placing concrete.

4). When concrete of the cross beam is placed, equivalent bending moment in the saddle must be taken into account. Reinforcement and prestressed reinforcement in cross beam must use the same ratio of reinforcement as prototype, and the prestressed reinforcement of saddle must also be laid in ribbed.

5). When making a loading beam, its bearing support is to be positioned in proportion to the prototype.

3.3 Measuring Point Placement of Model

Eleven stress testing sections are selected in model test according to the real conditions of the cable tower. The cross beam adopts the strain rossette, and the pylon uses the strain gage. The deformation tests are mainly used to test horizontal displacement and vertical displacement as well as lateral bracing deviations occurred in each construction phase under load, which is measured by the dial indicators.

3.4 Working Condition for Model Loading

As for the model test load, the vertical load is 75000KN and the horizontal load is 4600 KN according to design materials and similarity law of load [14]. In order to test the model's overloading capacity, 50% vertical overload is applied during the test. The model is loaded to 20%, 40%, 50%, 70%, 90%, 100% vertical load and then unloaded to 50% and 0% in sequence for three repeated times. After that, it is loaded to 100% vertical load + 50% horizontal load, 100% vertical load + 100% horizontal load, 150% vertical load + 100% horizontal load in sequence.

3.5 Analysis of the Model Test Results

The following results can be obtained through model test:

1). From the testing results of lateral bracing in construction phases, the following conclusion can be drawn: The lateral bracing stress varies as the construction phases change, whereas its stress is always small, which indicates that it is unnecessary to set pre-bias in actual construction.

2). The stress testing results of pylon suggest that the maximum compressive stress is -6.500Mpa and the maximum tensile stress is 0.053 Mpa in the process of vertical loading; the maximum compressive stress is -9.199Mpa, and the maximum tensile stress is 0.193Mpa in the process of horizontal loading; the maximum compressive stress is -10.456Mpa, and the maximum tensile stress is 0.893Mpa in the process of overloading.

3). When considering prestressed superposition in cross beam, the maximum compressive stress is -5.220Mpa and -5.570Mpa respectively in the process of vertical loading and horizontal loading. In the process of overloading, the maximum compressive stress is -4.02 Mpa without an tensile stress.

4). Under 50% vertical overload at 112500KN, there is no visible crack in the cable tower; in vertical load, horizontal load and overloading tests, the stepped loading of the tower model is of linear relationship, and the test data has good repeatability.

IV. Conclusions

1). According to the calculations of ultimate bearing capacity of cable tower of Liede Bridge, it is indicated that its ultimate bearing capacity is 320000KN and its safety factor is 4.27. Meanwhile, according to the model test verification, the following conclusion is obvious, that is, under 50% vertical overload at 112500KN, there is no visible crack in the cable tower; in vertical load, horizontal load and overloading tests, the stepped loading of the tower model is of linear relationship, and the test data has good repeatability. All suggests that the cable tower has good bearing capacity, rational design and high emergency capacity.

2). Proper constitutive model should be chosen accordingly when carrying out nonlinear finite element calculations of prestressed reinforced concrete structure, so as to ensure accuracy. Through calculations and analysis, the constitutive relation applied in this paper can give a better stimulation of actual failure process of prestressed reinforced concrete.

3). As for the model test with concrete, particle-sized aggregate concrete is used to satisfy the compaction of vibration, and the consistency of modulus of elasticity of the materials must be initially ensured to meet likelihood ratio.

4). When carrying out finite element stimulation and analysis of ultimate bearing capacity of reinforced concrete structure and pursuing the contradiction between its capacity in descent stage and astringency, the consideration of the crushing effect of concrete and stress-strain curve of inputted concrete in descent stage would unavoidably cause convergence calculation difficulties, making it hard to stimulate the whole course of construction stress. In order to get a better convergence for the analysis of the ultimate bearing capacity of reinforced concrete structure, it is advisable for us to adjust loading steps for trial calculations, whereas the techniques and methods concerning the selection of the steps remain to be further discussed.

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