Study on the Reconstruction of Existing Bridges with Composite Structure

Wen Yao¹*, Jianxun Ma¹ and Yuchen Zhang¹

¹School of Human Settlements and Civil Engineering, Xi’an JiaoTong University, Xi’an, Shanxi Province, 710049, China

*Corresponding author’s e-mail: yaow9610@163.com

Abstract. Cable-stayed bridges have their unique advantages, which are suitable for urban bridges with higher requirements for landscape improvement and upgrading. In the process of urban bridge renovation with landscape demand, the advantages of cable-stayed bridge in shape and structure are combined to provide more excellent scheme for urban bridge renovation. In this paper, the existing continuous girder bridge is reconstructed by adding cables. The internal force and displacement before and after structural renovation are calculated by Midas civil 2019. It can be seen that the internal force of the structure can be significantly improved by increasing the cables, and the maximum and minimum bending stress can be reduced by 40% and 20% respectively. Comparing and analyzing different retrofitting methods, the layout of cables has the most obvious effect on the maximum stress of the whole structure.

1. Introduction

In recent years, with the rapid development of cities, urban road and bridge facilities in China have developed rapidly, and traffic loads have been constantly rising. The structure of some existing bridges can no longer meet the reliability requirements of existing codes, so the reinforcement and transformation of existing bridges has become an urgent problem to be solved. The advantages of cable-stayed bridges include beautiful appearance, simple and clear cable surface, less visual interference to vehicles and pedestrians, changeable bridge facade, and superior structural performance, which are suitable for urban bridges with higher requirements for landscape improvement. Gradually, it is favored by bridge designers. In the process of urban bridge reconstruction with landscape demand, the advantages of cable-stayed bridge in shape and structure are combined to provide more excellent scheme for urban bridge reconstruction.

Liu Fengkui et al. introduced the concept of "influence degree of cable-load effect" in combination with the structural response of a single-tower two-span cable-stayed bridge under live load. This concept quantitatively analyses the essence of cable-stayed function of low-pylon cable-stayed bridge, and based on this, puts forward the parameter "characteristic parameter of low-pylon cable-stayed bridge", which can reflect the structural and mechanical characteristics of low-pylon cable-stayed bridge.

Based on the cable force influence matrix of cable-stayed bridge, Wang Xueming et al. established the cable force optimization model of low-pylon cable-stayed bridge with the minimum structural strain energy as the objective function. The cable force optimization analysis of Xiaoxihu Yellow River Bridge in Lanzhou and Xiamen Lake Bridge was carried out, and the following conclusions were obtained. In order to improve the mechanical performance of the main girder, it is necessary to optimize the initial tension of the stay cables. The optimized initial tension of the stay cables will make the bending moment diagram and deformation curve of the whole girder smoother, and the size of the initial tension of the...
stay cables has little effect on the cable-free zone optimization model of the side-span support.

2. Calculation theory of low-pylon cable-stayed bridge

Under the action of vertical load, the deflection of low-pylon cable-stayed bridge consists of four parts: the deflection of the main beam, the displacement caused by the elastic deformation of the cable, the vertical displacement of the main beam caused by the rotation of the main tower, and the elastic compression of the tower. The vertical displacements under unit loads are calculated respectively below.

2.1. Maximum Deflection of girder under unit vertical load

\[ \delta_{G_{\text{max}}} = \frac{L_G^3}{m \cdot E_G I_G} \]

in which, \( E_G \), \( I_G \), \( L_G \) is the elastic modulus, moment of inertia and span of the main beam, \( m \) is a coefficient determined by the boundary conditions of the girder. When the tower-beam pier is fully consolidated, \( m = 192 \); when one end of the tower-beam pier is consolidated and one end is articulated, \( M = 107.3 \); when the ratio of side span to mid-span is 0.5, \( m = 109.7 \); when the ratio of side span to mid-span is 0.6, \( m = 103.4 \).

2.2. Maximum vertical displacement of midspan cables under unit vertical load

vertical stiffness of midspan cables: \( K_{\text{c}} = E_c A_c \sin^2 \alpha / L_c \)

then the displacement under unit vertical load is,

\[ \delta_{\text{c, max}} = L_c / E_c A_c \sin^2 \alpha = H_T / E_c A_c \sin^3 \alpha \]

2.3. Vertical displacement of girder caused by rotation of tower under unit transverse load

The bridge tower subjected to transverse loads can be regarded as a beam with one end fixed and one end elastically supported. As shown in the figure, if the displacement of the elastic fulcrum and the spring stiffness are \( K \), the load at the end of the bridge can be regarded as a cantilever beam with one end consolidated. According to its deflection formula, the bridge tower can be regarded as a cantilever beam with one end consolidated.

The spring stiffness is provided by the cable, and the lateral stiffness of the cable is \( K = E_c A_c \cos^2 \theta / L_c \). Then,

\[ \Delta = \frac{H_T^3}{E_c A_c \cos^2 \theta \cdot H_T^3 / L_c + 3E_c I_T} \]

The rotation angle of the tower root is:

\[ \beta = \frac{\Delta}{H_T} = \frac{H_T^2}{E_c A_c \cos^2 \theta \cdot H_T^3 / L_c + 3E_c I_T} \]

Due to the rotation angle is relatively small, when the tower root rotates \( \beta \), it can be considered that the rotation angle of the main beam is \( \beta \), so the maximum displacement of the main beam span caused by the rotation of the tower is

\[ \delta_{T_{\text{max}}} = x \cdot \tan \beta \approx x \cdot \beta = \frac{H_T^3}{E_c A_c \cos^2 \theta \cdot \sin \theta \cdot \tan \alpha \cdot H_T^2 / L_c + 3E_c I_T \tan \alpha} \]

in which, assuming that the distance between the tower roots and the cable at the maximum displacement is \( x \), \( x = H_T / \tan \alpha \).

2.4. Vertical displacement caused by elastic compression of tower under unit vertical load

\[ \delta_T = \frac{H_T}{E_c A_c} \]

Comparing \( \delta_{G_{\text{max}}}, \delta_{\text{c, max}}, \delta_{T_{\text{max}}}, \delta_T \), we know that \( \delta_T \) is much smaller than \( \delta_{G_{\text{max}}}, \delta_{\text{c, max}}, \delta_{T_{\text{max}}} \). In order to
discuss conveniently, the main factors should be highlighted, so leaving it out. According to the previous description, the nominal stiffness formula can be obtained:

$$\gamma = \frac{1}{\delta_{G_T}} + \frac{1}{\delta_{G_{G_{max}}}} = \left( \frac{E_A \cos^2 \theta \cdot \sin \theta \cdot \tan \alpha}{H_T} + \frac{n E_g I_T \tan \alpha}{H_T^3} + \frac{E_A \sin^3 \alpha}{H_T} \right) + \frac{m E_{G_g} I_{G_g}}{L_{G_g}}$$

When analyzing the stiffness ratio of tower and beam, from $\delta_{G_{max}}$, $\delta_{G_T}$ we can see the law. But too many parameters make it inconvenient to highlight the key points. In order to study the relationship between tower and beam more conveniently and eliminate the influence of cable, only the tower and main beam are analyzed separately. The stiffness ratio formula of tower and beam:

$$\lambda = \frac{1}{\delta_{G_T}} / \left( \frac{1}{\delta_{G_{max}}} \right)$$

in which, $E_A$, $A_\alpha$, $\alpha$, $x_i$ is elastic modulus, section area, angle and horizontal projection of root I, respectively. $A_\theta$ is the area of the back rope. $E_{G_g}$, $I_{G_g}$, $L_{G_g}$ is the elastic modulus, moment of inertia and span of the main beam, respectively. $E_T$, $I_T$, $H_T$ is the elastic modulus, moment of inertia and height of the tower, respectively. The value method of M is as described above.

### 3. Finite Element Analysis

In this chapter, the structural is established by Midas civil 2019, and the bridge before and after the renovation is analyzed. The original structure uses full-prestressed concrete members with a large number of pre-stressed steel bars and ordinary steel bars. According to the requirements of full-prestressed components, the role of ordinary steel bars is not considered in calculation. The modified model of the structure is a beam with multi-point elastic support. In addition to the original support, the arrangement of cables is considered as a new elastic support.

#### 3.1. Model Parameter

The bridge is composed of two continuous beams, each of which has a span of 60 + 60m and a expansion joint in the middle. The structure consists of three double-column piers with diameter of 2m and cap height of 2.5m. There are six bored piles with diameter of 1.8m and length of 65m, 65m and 60m, respectively.

There are 694 nodes and 675 elements in the model. Elastic connection is used to simulate the actual bearing stiffness at the support. Rigid connection is used between pier cap and pile top. Elastic support is used to restrain the pile body restraint. Spring stiffness is calculated according to the mechanical parameters of foundation soil.

![Figure 1. Finite element model of the bridge](image)
3.2. Structural Characteristics after Modification

Structural transformation follows the basic principle of adding no reduction, that is, adding support and cables to the structure without changing the original structure, so as to improve the mechanical performance of the structure. The model is modified by adding elastic supports and cables. The original middle pier is regarded as a pylon. Five additional supports are added near the pylon with a distance of 5 m. The cable forces and angles of the cables are calculated in accordance with the table below.

Table 1. Height of tower and angle of cable

| Model | Height (m) | Angle (°) | Cable Force (kN) | Fx (kN) | Fz (kN) |
|-------|------------|-----------|-----------------|--------|--------|
| 1     | 15         | 31        | 2500            | 2142.9 | 1287.6 |
| 2     | 20         | 39        | 2500            | 1942.9 | 1573.3 |
| 3     | 25         | 45        | 2500            | 1767.8 | 1767.8 |

3.3. Bending Stress and Shearing Stress

According to the principle of comparison, the internal forces at three locations of one span, left and right, and in the middle of the span are selected for analysis. The total span of the whole structure is 4, and a total of 10 joints are selected for force analysis. In the finite element calculation results, the internal forces of the structure before and after the restructuring of the composite stress under the ultimate state are obtained as shown in Fig. 2 and Fig. 3- Fig. 5 respectively. The figure shows only the internal forces and displacements of a joint structure.

Figure 2. Composite stresses of unmodified structures

Figure 3. Composite stresses of modified structures 1

Figure 4. Composite stresses of modified structures 2

Figure 5. Composite stresses of modified structures 3
Extract 0, L/8, L/4, 3L/8, L/2, 5L/8, 3L/4, 7L/8, L respectively, where L is a joint length, i.e. 120 m. The bending stress, shearing stress of all the nine nodes are shown below.

4. Conclusion

Through the analysis of the internal force of the structure under the load combination, it can be seen that the new cable can significantly improve the internal force of the structure. The larger the angle of the cable, the greater the improvement of the internal force. The minimum bending stress decreases from -10.20 MPa to -8.63 MPa and the maximum from 7.62 MPa to 4.58 MPa. The minimum value was reduced by 15.4% and the maximum value by 39.9%. The minimum shear stress decreases from -30.7 MPa to -22.7 MPa and the maximum from 30.0 MPa to 17.2 MPa. The minimum value decreased by 26.1% and the maximum value decreased by 42.7%. Adding new cables has the most obvious effect on the maximum value of bending stress, which can reduce the maximum value by about 40% and the minimum value by about 20%.

Comparing different modification methods, the influence of cable angle on structure can be reflected by stress changes. Three modification methods are adopted, the angle is 31 degrees, 39 degrees and 45 degrees, respectively. The minimum bending normal stress changes from -8.5 MPa to -8.0 MPa and the maximum from 4.6 MPa to 3.6 MPa. The minimum shear stress changes from -24.9 MPa to -22.7 MPa, and the maximum from 20.7 MPa to 17.2 MPa. It can be seen that the change of the maximum
shear stress is more affected by the cable. Through this study, we can know that adding cables can significantly improve the stress state of the structure, and can significantly reduce the internal force of the structure. How to quantitatively analyze the influence of cable force optimization and layout on the structure and its dynamic characteristics still needs further efforts of researchers.

Acknowledgments
The author wish to thank for the financial support provided by this project named Study on the Mechanism of Impact Resistance of Composite Composite Structures (whose number is YZA2018Ky01). Thank my mentor, Professor Ma Jianxun, for his help throughout the research process, including not only providing engineering information, but also providing scientific research environment and tireless guidance. At the same time, I would like to thank my colleague Zhang Yuchen for his contribution in this paper. At the same time, I would like to express my heartfelt thanks to all the reference authors in this paper, and thank you for your contribution on the road of bridge research.

Reference
[1] Wang Yzh, Shu H. (2017) On the Current Situation and Development Trend of Urban Bridges in China. Jiangxi Building Materials, (7):184-185.
[2] Chen Cch. (2005) Research on the Core Problems of Design Theory of Low Tower Cable-stayed Bridge. Tongji University.
[3] Liu Fk, Lin Pzh, Chen Q, et al. (2003) Optimizing initial tension of cables for low-pylon cable-stayed bridges. Journal of Lanzhou Jiaotong University, 22(4): 64-67.
[4] Zhang Zm. (2016) Analysis of the Trend of Urban Bridge Structural Renovation Design in the New Period. Jiangxi Building Materials, (24): 158-159.
[5] Kang W. (2004) Structural Analysis of Some Cable-stayed Bridges of Xiaoxihu Yellow River Bridge Railway Standard Design, (11): 88-90.
[6] Zhang Hy. (2006) Analysis and Research on the Structural System of Three-Tower Partial Cable-stayed Bridge . Urban Road and Bridge and Flood Control, (6): 44-47.
[7] Liu Fk, Lin Pzh, Chen Q, et al. (2004) Study on characteristic parameters of low-pylon cable-stayed bridge . Engineering Mechanics, 21 (2): 199-203.
[8] Chen Xch, Yu Ls, Wu Gf, et al. (2003) Seismic analysis of Xiaoxihu Partial Cable-stayed Bridge in Lanzhou. Journal of Lanzhou Jiaotong University, 22(3): 42-44..
[9] W. S. Shum, C. F. Tsang, Z. Lin. (2008) Complete function collocation method for solving preliminary cable-stayed bridge pretension forces. Bridge Structures, 4(2):59-74.