

Internal Force State Recognition of Jiujiang Bridge Based on Cable Force-displacement Relationship

Weifeng Wang, Guoqing Huang, and Xianwei Zeng

Abstract—The nearly 21-year-old Jiujiang Bridge, which is suffering from uneven line shape, constant great downwarping of the main beam and cracking of the box girder, needs reinforcement and cable adjustment. It has undergone cable adjustment for twice with incomplete data. Therefore, the initial internal force state of the Jiujiang Bridge is identified as the key for the cable adjustment project. Based on parameter identification by means of static force test data, this paper suggests determining the initial internal force state of the cable-stayed bridge according to the cable force-displacement relationship parameter identification method. That is, upon measuring the displacement and the change in cable forces for twice, one can identify the parameters concerned by means of optimization. This method is applied to the cable adjustment, replacement and reinforcement project for the Jiujiang Bridge as a guidance for the cable adjustment and reinforcement project of the bridge.

Keywords—Cable-stayed bridge, cable force-displacement, parameter identification, internal force state

I. INTRODUCTION

THE internal force state identification method for the existing structure can be divided into the local identification method and the integrated identification method. According to the dependence of the characteristic quantity required for the state identification on the structural model, it can be divided into the model-based identification method and the model-free identification method; by identification strategy it can be divided into the unretrieval identification method, the retrieval identification method and the hybrid identification method [1,2].

The currently adopted retrieval identification method is mainly based on the model updating theory. Model updating originates from the difference between the theoretical and experimental results of finite elements. Its basic idea is: use the response information of the actual measurement of structure to amend the initial finite element model to better reflect the mechanic behaviors of structure.

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The model updating method mainly include the matrix amendment method proposed in the early stage and the parameter amendment method proposed in recent years, namely parameter identification. As the basis of structural state identification, the model updating and parameter identification theory is essentially an inverse problem, which can come down to an optimization problem to be solved [3].

The main span of the main bridge of the Jiujiang Bridge is designed to be a cable-stayed bridge under the single-tower double-cable-plane harp-shaped prestressed concrete rigid pier-tower-beam joint system, with the tower 81m above the deck as an H-shape pylon with horizontal partition and the girder as a cantilever assembly prestressed concrete box girder, with DM button-head anchorage. The main tower has 18 pairs of stay-cables on each side, totally 144 cables; the cable protection adopts hot-extruded PE sheath method with the sheath made on the site. The deck pavement adopts the 8-centimeter-thick waterproof concrete. The layout of the overall structure of the bridge is shown in Figure 1. The cross section of the girder is shown in Figure 2. The Jiujiang Bridge has run for about 21 years ever since it was opened to traffic in June 1988. It has undergone cable adjustment for twice with incomplete data. The bridge underwent the girder elevation test and the cable tension test respectively in July 2000 and August 2008, at similar test time and under similar environments. The main problems on the box girder of the superstructure of the cable-stayed bridge are:

1) Uneven line shape: The line shape is uneven. The cable forces of the single tower symmetrical structure are greatly asymmetric and zigzagging lengthwise and uneven in the cable forces of the 4 ropes of each cable broadwise.

2) Great downwarping of the girder: Two years after completion of construction (May 1990) and prior to the cable adjustment, for the girder crossing to the north (by the Jiujiang River), the center line of Cable Point 11 suffered from 16.6-centimeter downwarping (even on upstream and downstream, the same below), and for the girder crossing to the south (beside the Zhanjiang city), the center line of Cable Point 10 suffered from 14.4-centimeter downwarping. And 10 years later (May 2000) and prior to the cable adjustment, the two points suffered from further downwarping by 3.3cm and 4.3cm. And 17 years later, the elevations of Cable Point 15 and of Cable Point 16 by the Jiujiang River dropped by a maximum of

1.9cm, compared with the elevation in August 2000.

3) Cracking of the box girder: The cracks in the diaphragm plate are generally scattered via the manhole, especially the cracks running through the diaphragm plates in the two wing chambers of the box girder are densely distributed. Most of the cracks in the diaphragm plates of the two middle chambers are on the upper part of the manhole, and some are extended to the lower part of the manhole; the causes of the cracking on the top plate, the base plate and the web plate are complicated.

In view of the current state of the Jiujiang Bridge, it needs reinforcement and cable force adjustment. For the cable-stayed bridge running for many years, with the change of its internal force state caused by such negative factors as loading, fatigue, corrosion and the natural aging and damnification accumulation of materials, the structural parameters of the running bridge must have deviations from the design value. Therefore, to adjust the cable force of the cable-stayed bridge that has run for years, the first thing to do is to solve the current structure's internal force state identification problem, which is especially important for a bridge lack of or missing relevant data on design or construction.

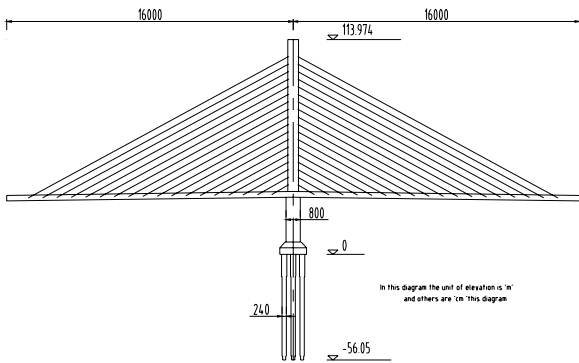


Fig. 1 Jiujiang Bridge Main Bridge Chart.

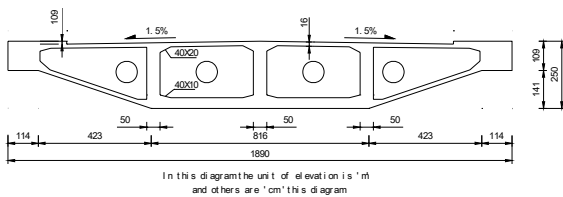


Fig. 2 Jiujiang Bridge girder cross-section diagram

II. PARAMETER IDENTIFICATION METHOD BASED ON STATIC TEST DATA

The basic principle of state identification is: The response of structure (natural frequency, modal shape, strain, displacement and the corresponding derived information) is the function of the physical properties (rigidity, mass, damp, boundary condition, and so on) of structure. So the change of structural parameters will cause the change of structural response. By comparing the observed structural response with the baseline,

one can get the relevant information on the key parameters of the structure, so as to realize the state identification of the structure [4,5].

Discretizing the structure to a finite element model with n degree of freedoms (DOF), and the equation of static equilibrium is [6,7,8,9] as follows:

$$K(p)U = F \quad (1)$$

where $K(p)$ is the overall stiffness matrices of the structure, and p , U and F are the identifying parameter vector, the static displacement vector and the load vector of the structure respectively. Accordingly, the static displacement vector (U) of the structure under the load F and the strain response vector ε are:

$$\begin{aligned} U &= K(p)^{-1}F \\ \varepsilon &= BK(p)^{-1}F \end{aligned} \quad (2)$$

where B represents the strain-displacement relationship matrix.

Similar to the dynamic response test, loading and testing are available for some degrees of freedom only in the actual application. In addition, the loaded and tested freedom degrees are generally different freedom degree sequences. Suppose the structural responses under nlc linearly independent conditions are tested. For Working Condition i , let the number of the degrees of freedom of displacement response test be m , the number of the degrees of freedom not measured be l , the structural load vector be F_i and the corresponding displacement and strain test values are U_m^i and ε_m^i . Under Working Condition i , the structural static response's theoretical values are respectively U_i and ε_i . In order to get the analytic result corresponding to the test result, U_i can be divided into the determined component U_{Ti} (m -dimensional) and the undetermined component U_{Ni} (l -dimensional), and accordingly F_i can be divided into F_{Ti} and F_{Ni} , when Equation (1) can be changed into the following equation:

$$\begin{bmatrix} K_{mm} & K_{ml} \\ K_{lm} & K_{ll} \end{bmatrix} \begin{Bmatrix} U_{Ti} \\ U_{Ni} \end{Bmatrix} = \begin{Bmatrix} F_{Ti} \\ F_{Ni} \end{Bmatrix} \quad (i = 1, 2, \dots, nlc) \quad (3)$$

Equation (3) can be changed into the following equation:

$$U_{Ni} = K_{ll}^{-1}(F_{Ni} - K_{lm}U_{Ti}) \quad (4)$$

Substitute Equation (4) into Equation (3) to obtain U_{Ti} .

$$U_{Ti} = (K_{mm} - K_{ml}K_{ll}^{-1}K_{lm})^{-1}(F_{Ti} - K_{ml}K_{ll}^{-1}F_{Ni}) \quad (5)$$

For simplicity, take Equation (5) as follows:

$$U_{Ti} = H_u^i K(p)^{-1} F_i \quad (6)$$

Similarly, the corresponding determined part's strain ε_{Ti} is in a similar form:

$$\varepsilon_{Ti} = H_\varepsilon^i BK(p)^{-1} F_i \quad (7)$$

where H_u^i and H_ε^i are respectively the displacement matrix and

the strain observation matrix.

Then the displacement vector and strain residual vector of Working Condition i are respectively as follows:

$$E_u^i(p) = H_u^i K(p)^{-1} F_i - U_m^i \quad (8)$$

$$E_\varepsilon^i(p) = H_\varepsilon^i B K(p)^{-1} F_i - \varepsilon_m^i \quad (9)$$

During the actual test of the structure, there are errors about the displacements and the strain test data and loading, which might vary with the degrees of freedom in testing and loading. Therefore, for every working condition, one can import the displacement weighted matrix W_u , the strain weighted matrix W_ε and the load weighted matrix W_F respectively according to the precisions of different displacement measuring points, strain measuring points and load working conditions. Meanwhile, in view of the great difference between different test data in terms of order magnitude, to prevent the test data of small magnitude from drowning in the that of larger magnitudes, one can introduce the magnitude weighted matrix W_{ss} . W_u , W_ε , W_F and W_{ss} are all diagonal matrixes. The diagonal elements of the matrixes are the weights of the observed quantities under different working conditions in the corresponding vectors.

After weighed correction, the displacement and strain residual vector corresponding to Working Condition i can be expressed as follows:

$$\tilde{E}_u^i(p) = W_{ui} E_u^i(p) W_{Fi} \quad (10)$$

$$\tilde{E}_\varepsilon^i(p) = W_{\varepsilon i} E_\varepsilon^i(p) W_{Fi} \quad (11)$$

Join the displacements and strain residual vectors of the structures under different working conditions end to end to obtain the overall residual vector of the static response of the structure ($\tilde{E}_{st}^i(p)$). To keep the displacement data among the residual vectors in conformity with the magnitude of the strain data, one can introduce the magnitude weighted matrix $\tilde{E}(p)$ for correction.

$$E_{st}(p) = W_{ss} \tilde{E}(p) \quad (12)$$

Suppose the dimensionality of all the static response test data under all working conditions is SM , and let the minimum variance solutions be the solutions of the unknown parameters, and the structural parameter identification problem based on static response can be attributed to the following optimization problem:

$$\min J(p) = \frac{1}{2} E_{st}(p)^T E_{st}(p) = \frac{1}{2} \sum_{i=1}^{SM} e_i^2(p) \quad (13)$$

$$s.t. \quad p^L \leq p \leq p^U \quad (14)$$

where $e_i(p)$ represents Element i of SM dimension vector $E_{st}(p)$.

III. CABLE FORCE-DISPLACEMENT RELATIONSHIP OF THE GIRDER OF EXISTING CABLE-STAYED BRIDGE

The strain energy of the structure can be expressed as follows^[10]:

$$U = \int_0^1 \frac{M^2}{2EI} dx + \int_0^1 \frac{N^2}{2EA} dx + \int_0^1 \frac{kQ}{2GA} dx \quad (15)$$

Regardless of the shear stress and under the finite element concept, the structure of the strain energy can be expressed as follows:

$$U = \sum_{i=1}^m \frac{l_i}{4E_i I_i} \{ (M_i^l)^2 + (M_i^r)^2 \} + \sum_{i=1}^m \frac{l_i}{4E_i A_i} \{ (N_i^l)^2 + (N_i^r)^2 \} \quad (16)$$

where m represents the number of beam elements, and l_i , E_i , I_i , A_i represents the length, the modulus of elasticity, the second moment of area and the sectional area of Unit i respectively; M_i^l and M_i^r are respectively the left and right bending moments Unit i ; N_i^l and N_i^r are respectively the left and right axial forces of Unit i .

The bending moment and axial force will be expressed as the function of external force as follows:

$$\{ M, N \}^T = B F_{DLP} + C T \quad (17)$$

where F_{DLP} represents the dead load, the live load and the prestress; T represents the cable force. Matrix B and Matrix C are determined by unit characteristics and form of structure. Without any constraint conditions, $\partial U / \partial T_i = 0$ means that the mutual displacement of certain Lasso incision to the unknown cable force T_i is 0, hence the equation can be established as follows:

$$\Phi T = -u_{DLP} = \delta \quad (18)$$

where Φ represents the influence matrix, Row i and Column j represent the variation of the No. i target value (including displacement, stress and reaction force) after the No. j stayed-cable force unit changes, and δ represents the actual variation of the target value. The above equation is actually a equilibrium equation in force method, with Φ as the flexibility matrix; u_{DLP} is the displacement vector caused by other outer loads; $\delta = -u_{DLP}$ [11].

Judging from the above equation, the change of the cable force is corresponding to that of displacement, which is applied to the parameter identification of the cable-stayed bridge in this paper. If the variations of cable force and displacement are measured at the same time, the unknown parameters will be worked out by means of optimization.

IV. JIUJIANG BRIDGE PARAMETER IDENTIFICATION BASED ON THE FORCE-DISPLACEMENT RELATIONSHIP

As described in the previous section, regardless of the influence of the relaxation of the cable and the temperature on

the cable force and the line shape, the changes in outer loads will cause the corresponding displacements, and the linear changes in the cable-stayed bridge girder is caused by the changes in cable force, which is applied to the girder parameter identification in this paper.

3.1 Selection of the Parameters to Be Identified

According to the sensitivity of different parameters, correcting the parameters relatively sensitive to the displacement changes helps increase the model correction efficiency and reduce workload. Based on the parameter sensitivity analysis, the girder stiffness is the key parameter affecting the girder deformation behaviors. As it is hard to work out the accurate value of the actual girder concrete initial elastic modulus, let the beam’s cross-section area and moment of inertia constant (calculated in accordance with the design drawings) and the elastic modulus of concrete as a correction parameter. As there are different types of girder sections in the midspan, the side span and the tower root, one can divide the girder lengthwise into six regions (see Figure 3), giving each region a corrected parameter value, namely the concrete elastic modulus. And the variables and the range of the parameters to be identified are shown in Table 1.

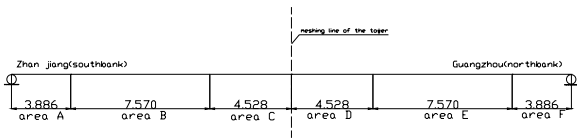


Fig. 3 The identification region of the main beam stiffness (unit: cm)

TABLE I
DESIGN VARIABLES AND THE RANGE OF PARAMETERS TO BE IDENTIFIED

Serial number	Description variable	Design variable name	Initial value of variable	Variable range
1	Main beam regional A modulus coefficient	BEAM_EA	1.0	[0.50,1.50]
2	Main beam regional B modulus coefficient	BEAM_EB	1.0	[0.50,1.50]
3	Main beam regional C modulus coefficient	BEAM_EC	1.0	[0.50,1.50]
4	Main beam regional D modulus coefficient	BEAM_ED	1.0	[0.50,1.50]
5	Main beam regional E modulus coefficient	BEAM_EE	1.0	[0.50,1.50]
6	Main beam regional F modulus coefficient	BEAM_EF	1.0	[0.50,1.50]

3.2 Determination of the Objective function

Upon determination of the parameters to be identified, the bridge parameter identification will shift to structural parameters optimization. The cable-stayed bridge parameter identification process adopts the elevation data and the cable

force data of the structure measured in 2000 and 2008 respectively, taking the changes of the cable force as the non-independent variables in parameter optimization, so that the model’s displacement values can be close to the measured value. The optimization process in this paper is done in the optimal design module in ANSYS.

In the model, let the changes in the girder displacement caused by that in the measured cable force be U_{ii} (the calculated displacement) and U_{ai} be the design variable , and define the absolute value of the relative error between the calculated displacement and the measured displacement as the objective function as follows:

$$objection_function = \min \left(\frac{1}{36} \sum_{i=1}^{36} \left| \frac{U_{ii} - U_{ai}}{U_{ii}} \right| \right) \quad (19)$$

where U_{ii} represents the measured displacement (elevation of 2008 – elevation of 2000) , and U_{ai} represents the calculated displacement.

3.3 Parameter Identification and Optimization Results

The values of the design variables under optimal results are shown in Table 2, and the comparison between the calculated displacement and the measured displacement of each measuring point after parameter optimization is shown in Figure 4. As is shown in Figure 4, there is a large error between the theoretical displacement and the measured displacement, and the corrected displacement and the measured displacement result agree well after parameter identification. As is shown in Table 2, the regional elastic modulus coefficients range from 0.782 to 0.854 with an average of 0.812 after parameter identification, and the variables are not so discrete and almost symmetric after parameter optimization. The girder stiffness drops by an average of about 18.8%.

In order to check the impact of the measured displacement errors on the parameter identification results, one can increase and decrease the measured displacement value U_{ii} by 5% respectively for parameter optimization. The results show that the average of the elastic modulus coefficient BEAM_E will drop by 3.16% when U_{ii} is increased by 5% and rise by 3.94% when U_{ii} is decreased by 5%. This means that importing a small error will not cause a large export error and that the error of the measured displacement U_{ii} does not affect the identification results much.

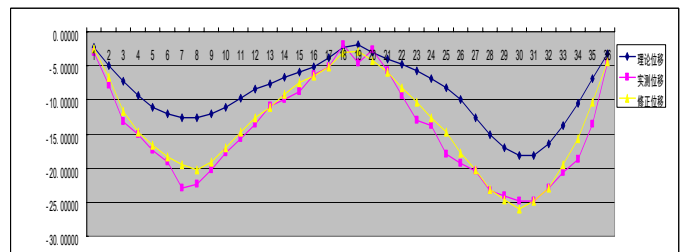


Fig. 4 Measured displacement increment comparing the calculated values after identification (unit:mm)

V. DETERMINATION AND EVALUATION OF THE CURRENT INTERNAL FORCE STATE OF THE BRIDGE

Based on the results of the parameter identification, use Midas/Civil2006 to establish the finite element correction model after cable replacement of the whole bridge, so as to analyze the bridge state, including the dead load and the (running) internal force analysis. The modeling adopts the parameters obtained after identification.

TABLE II
THE OPTIMIZATION RESULTS OF DESIGN VARIABLES

Serial number	Description variable	Initial value of variable	Optimization results
1	Main beam regional A modulus coefficient	1.0	0.790
2	Main beam regional B modulus coefficient	1.0	0.854
3	Main beam regional C modulus coefficient	1.0	0.829
4	Main beam regional D modulus coefficient	1.0	0.813
5	Main beam regional E modulus coefficient	1.0	0.805
6	Main beam regional F modulus coefficient	1.0	0.782

At the stage of normal use limit state, under the short-term effect combination, the girder's maximum stress (forward direction) is 0.87Mpa, found at the lower edge near Cable 15 on the Zhanjiang side, with the crack checking value exceeding the standard allowable values; under the standard combination, the minimum compressive stress is -15.77 MPa (forward direction), close to the standard allowable values -16.2 MPa. The working state of the girder is unfavorable, which demands for reinforcement and cable adjustment.

VI. CONCLUSIONS

1). Based on the static test data, this paper verifies that the changes in cable force are corresponding to that in displacement, which is applied to the cable-stayed bridge parameter identification. If the variations of cable force and displacement are measured at the same time, the unknown parameters will be worked out by means of optimization. The paper proposes determining the initial state of the internal force of the existing cable-stayed bridge by means of parameter identification according to the "cable force – displacement" corresponding relationship.

2). Take the establishment and correction of the Jiujiang Bridge finite element model for example. Adopt the parameter identification method according to the "cable force – displacement" corresponding relationship. Simplify the identification of internal force into the girder stiffness identification. The calculation results show that the stiffness of the Jiujiang Bridge drops by about 18.8%, compared with the theoretical values. Under the standard combination, the minimum compressive stress is -15.77 MPa (forward direction), close to the standard allowable value -16.2 MPa. The working state of the girder is unfavorable, which demands

for reinforcement and cable adjustment. The internal force results obtained after identification can be used as an important basis for the follow-up cable force adjustment of the bridge.

3). This paper simplifies the identification of internal force into the girder stiffness identification in the actual project. The changes in the internal force state of the bridge structure include: the redistribution of internal force due to the changes in material properties (e.g. material creep, plastic properties redistribution, etc.), the changes in internal force state due to boundary conditions (e.g. support settlement, expansion joint blockage, etc.), the changes in internal force state due to overload (e.g. serious overload, ship collision, strong wind, earthquake, etc.). It can be seen that the changes affecting the internal force state of the cable-stayed bridge are diversified. Therefore, the multi-parameter identification is still to be further studied and improved.

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