11th International Conference on Vibration Problems
Z. Dimitrovová *et al.* (eds.)
Lisbon, Portugal, 9-12 September 2013

MODAL TESTING AND FE MODEL UPDATING OF A FOOTBRIDGE STRUCTURE

Zhou Chen*[1], Quan S. Yan[1], Bu Y. Jia[1], Xi J. Ye[2]

[1]School of Civil Engineering and Transportation, South China University of Technology, Guangzhou , 510640,China
gscz19861985@126.com, cvqshyan@scut.edu.cn, jbyretop@126.com,

[2]Guangzhou Municipal Group Co. ltd, Guangzhou, Guangdong, 510640, China
xijunye.scut@gmail.com

Keywords: Ambient Excitation, Landscape Suspension Footbridge, Finite Element Model, Vibration Testing, Modal Parameter Identification, Model Updating.

Abstract. *With the propel of urbanization and the use of new materials, more and more big span soft pedestrian bridges are built. However, it is easy to cause the problem of footbridge vibration excited by walking. So it is necessary to study dynamic characteristic of footbridge. Although,the FE numerical calculation and analysis of bridge modal characteristics have been applied for a long time. Great progress has been made as well. Due to the influence of uncertainty factors, such as material properties, boundary conditions and accessory structure, there are big differences between the design stage and construction stage as for these factors. So it is of great necessity to study vibration testing of footbridges after construction. The paper makes an analysis on FE model and has a dynamic testing in natural excitation based on a landscape suspension footbridge in a park. By setting different reference DOFs in each group for data acquisition and applying the dynamic testing technology for bridge dynamic signal, the parameter identification is studied with modal parameter identification procedure. Moreover, the computed results are contrasted with the computation of a 3D finite element model. The FE model was adjusted with some parameters of the footbridge. At last, to determine the precise boundary conditions and elastic modulus of concrete, dynamic characteristics analysis of the footbridge was evaluated in this paper.*

1 INTRODUCTION

As the large span suspension footbridge structure is soft, its structure natural frequency of vibration tends to be low. Within the scope of the pedestrians stride frequency, footbridge structure vibration and even resonance are easily induced by pedestrian loads. Dynamic characteristics study is required when its natural frequency reaches to 1.3 HZ in transverse and 5 HZ in vertical [1]. However, in the process of footbridge construction and use, mostly due to the influence of boundary conditions, stress stiffening, initial stress, Density and the Young's modulus of concrete, the dynamic characteristic value differs from measured values, which is calculated by the FE [2]. Therefore, it is necessary to modify the FE model in order to get the FE model which is better consistent with the actual situation. Based on Guangzhou No.3 Longtan park footbridge, firstly the paper discussed the random testing process and result of the footbridge under the environmental motivation. And then the three-dimensional FE model is established with the FE software ANSYS to analyze the dynamic characteristics of the bridge after it is built. Moreover, it makes contrast with the measured values. At last, the FE model is modified according to the measured values.

2 THE GENERAL SITUATION OF THE ENGINEERING

No.3 Longtan park footbridge is the two-tower, single-span, and self-anchored suspension bridge. Its elevation schematic diagram is shown in Figure 1. The total length of the bridge reaches 110 m. Its span arrangement is 20 + 70 + 20 m. In addition, mid-span loads are bore by the main cable, which is anchored on the end-girder of side-span . The longitudinal slope of the bridge is 6%, the convex curve radius R = 500 m, 1:10 of sag ratio, sag f = 7m. The main cable on the mid span is 2.5 m in height to the girder. The separation distance of suspenders is 3 m.

The main tower is 13.657 m high and built in a shape of A by adopting curve modeling. It is composed of two tower columns. Besides, 1.5m high collar beam is set on the point of 1.5m to the tower top. In addition, cable saddles are set on the beams. The main span of girder adopts π cross section. Beams are set in the middle of suspension centre. And the beams are in H-shape cross section. The side span adopted box-section when main girder pass through the main tower. The material of its girders is C50prestressed concrete.

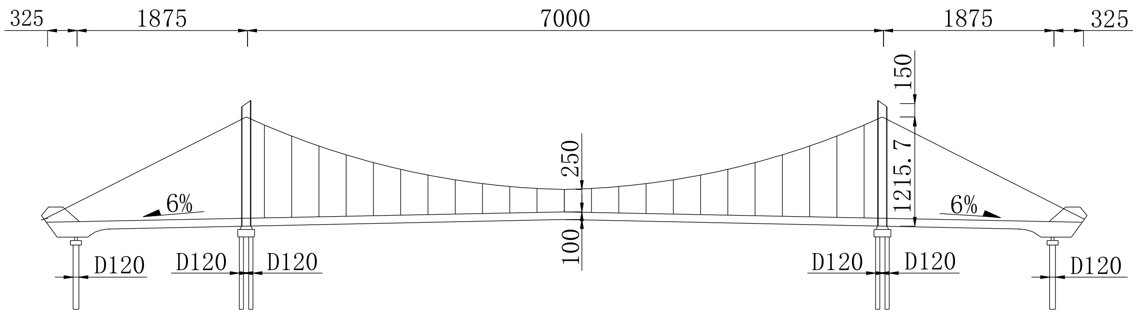


Figure 1: Elevation diagram of Longtan footbridge

3 INITIAL FE MODELLING

The load-carrying components of suspension bridge include cable, beam, tower, and pier. The FE structural simulation focuses on the mass and stiffness of structure as well as simulation of boundary condition [3].

3.1 The simulation of structure

The girder and main tower adopt three-dimensional beam element simulation. As the main cable and suspender are tension components, the LINK10 unit simulation is adopted, which is defined as only tension in the paper [4]. As for nonlinear effects of main cable sag, its horizontal projection length is 3 m. So, the nonlinear effect can be ignored.

3.2 Processing of boundary condition

The suspender and girder of Longtan bridge are connected by rigid arm. The elastic modulus of rigid arm is set 15 times of steels in modelling [5]. According to the specific situation, constraint handling of bridge tower and main girder are the constraint horizontal and vertical displacement of the girder on bridge tower. Longtan bridge's main cable and the bridge tower are connected by the main cable saddle. So, the nodal point on the connection between main cable and bridge tower are built by coupling. As the underpinning of the main tower reaches the rock, the bottom of main tower and end-girder of side-span should be consolidated and constrained UY and UZ on bridge pier.

3.3 Processing of stress stiffen and gravity stiffness

As for the suspension bridge, the out-of plane structure stiffness is influenced by the in-plane stress state of the cable. The coupling between in-plane stress and transverse stiffness is called stress stiffen [3]. Gravity stiffness of suspension bridges is provided by the initial tensioning force of main cable. In general, axial stiffness of the main cable is larger than flexural rigidity of the girder [6]. So, gravity stiffness should be taken into consideration in the process of making the FE model. To be more specific, initial strain is imposed on the main cable so as to the main cable sharing the initial stiffness. Static calculation for the structure is calculated first. And then the gravity stiffness of main cable is adjusted by adjusting the initial strain of the main cables. Thus, the line type and internal force of bridge under the completion state should meet with the following conditions: (1) minimum deflection of the bridge under the effect of dead load; (2) the minimum internal force of main girder under the effect of dead load. The panel points of mid span are regarded as reference points in the paper. when the initial strain of main cable is 0.00128, the deflection of mid span panel point is 0.149 mm. Axial force of main beam is 6208 KN, which is considered as an ideal model for modal analysis. In the FE model, there are 255 nodes, 291 units, 37 main girder units, 92 main cable units, 46 suspender units, 66 bridge tower units, 50 rigid arm units. The FE model of whole bridge is shown in Figure 2.

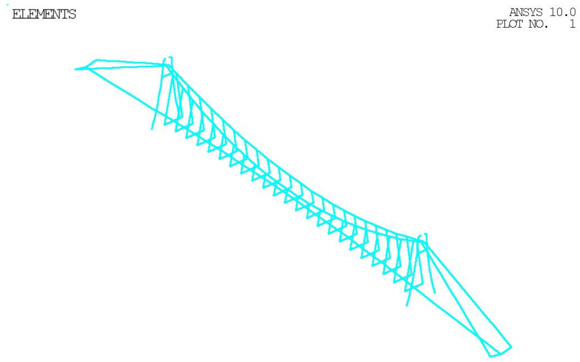


Figure 2: Spatial FE model of Longtan footbridge

4 DYNAMIC CHARACTERISTICS TEST OF LONGTAN BRIDGE BASED ON THE RANDOM ENVIRONMENT INCENTIVE

Dynamic characteristics test of the bridge is based on the random environment incentive method. The modal testing instruments are 99-1 type vibration pickup and 941 type 8 line amplifier made by institute of engineering mechanics of China seismological bureau and the AVANT dynamic data acquisition system made by Hangzhou Yihen Science and Technology Company. It is tested on March 20, 2013. Dynamic monitoring point arrangement is shown in Figure 3. Taking V7, V20 as reference points, each group tests six points. The sampling frequency is set 160 Hz. The sampling time is 20 mins long for each group. The realistic picture of the whole bridge is shown in Figure 4. MATLAB is adopted based on peak value method (PP) self-programming to process vibration signal. The method is simple and convenient. It is able to accurately identify the frequency and vibration mode of the results in high computing speed.

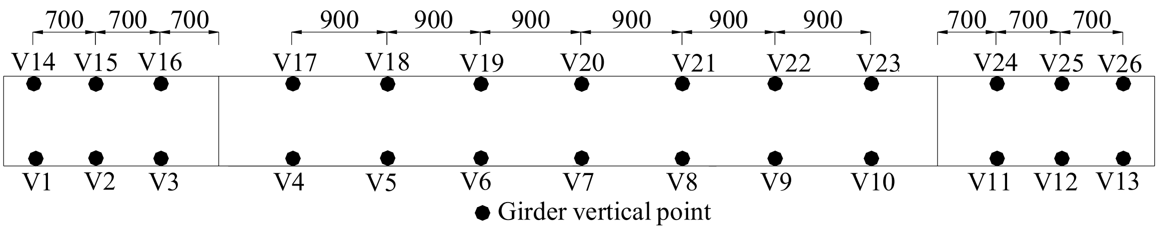


Figure 3: Main beam vertical measuring point layout

Figure 4: Realistic graphics of Longtan footbridge

5 COMPARISON ON THE FE DYNAMIC CALCULATION RESULTS AND THE MEASURED RESULTS

The vertical vibration characteristic of the bridge is merely tested in the test, so the comparison of the vertical vibration characteristics is studied here, as shown in Table 1.

Modal order	Actual frequency/Hz	Calculated frequency/Hz	Mode of vibration
1	1.025	1.481	inconformity
2	1.337	2.056	inconformity

Table 1: Comparison on the actual frequency before revision and theoretical frequency

The above table only lists the first two pair ratio of vertical measured frequency and calculated frequency of the girder. According to the Table 1, the measured dynamic characteristics of the structure are not conformed to vibration mode. The natural frequency of vibration value and calculating natural frequency of vibration are also in big difference. Therefore, revision on FE model is required.

6 ADJUSTMENT BASED ON THE SENSITIVITY FE MODEL

6.1 The to-be corrected structure parameters

Errors on the FE model parameter of suspension bridge are generally composed of the boundary conditions, girder, Young's modulus and Density of main tower, the initial strain of main cable, main cable and the axial stiffness of suspender. However, the cross-sectional area of the main beam is accurate simulation. So, the cross section area of the main girder is not amended. As each of the parameters have different influence on the structure dynamic characteristics [7]. The parameter sensitivity is analyzed firstly. Moreover, FE model is modified. Finally, to-be corrected parameters (shown in Table 2) are decided.

Corrected section	Structure parameter	Initial estimate vale
Girder	Young's modulus E_l	3.45×1010Pa
	Density ρ	2600kg/m3
Main tower	Young's modulus E_t	3.45×1010Pa
	Density ρ	2600kg/m3
Main cable	Initial strain ε	0.00128 ε
	Axial stiffness $E_l A$	1808605.5KN
Suspender	Axial stiffness $E_g A$	84328KN

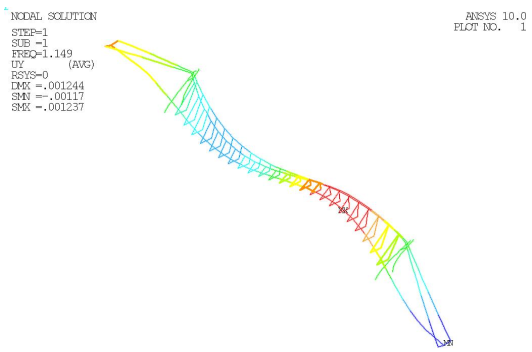
Table 2 : To-be corrected structure parameter

6.2 The correction of a boundary condition

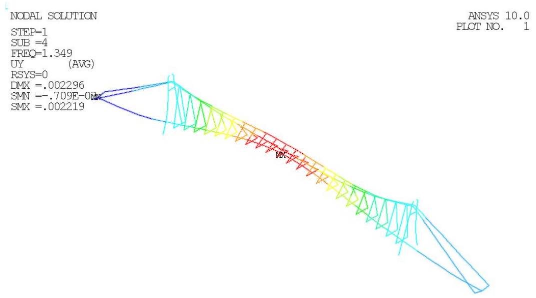
Due to the lower location the bridge, in the using process of subsequent park, side span beam-end is partly buried by surrounding soil mass. However, it is not completely consolidated. So, in the correction process of boundary conditions, the end-girder of side-span constraints can be processed into released around y axis, which is rotatable. The contrast of revised boundary conditions of each order frequency calculation value and the measured frequency is shown in Table 3. The models of vibration are shown in Figure 5.

Modal order	Measured frequency/Hz	Calculated frequency /Hz	Deviation /%	The model of vibration
1	1.025	1.149	12.09	the First antisymmetric lateral bending girder
2	1.267	1.349	6.47	the Second antisymmetric lateral bending girder
3	1.697	1.773	4.48	the Third antisymmetric lateral bending girder
4	2.120	2.239	5.61	the Forth antisymmetric lateral bending girder

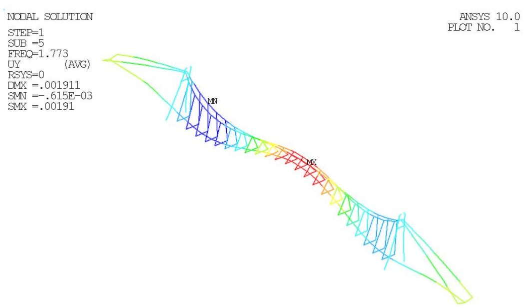
Table 3 : Comparison between the revised measured frequency and calculated frequency of boundary conditions



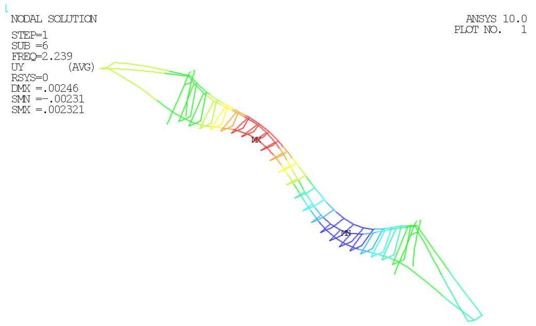
a) First modal shape（f=1.149Hz）



b) Second modal shape（f=1.349Hz）



c) Third modal shape（f=1.773Hz）



d) Fourth modal shape（f=2.239Hz）

Figure 5: Calculation mode figure on the boundary condition of Longtan bridge after revised

According to Table 3 and Figure 5, the revised measured vertical vibration characteristics are roughly consistent with calculated dynamic property. They are in the same mode of vibration. In addition, the first frequency is 12.09%. The second, third and fourth frequency differs about 5%. It proves that the process of preliminary modeling of end-girder of side-span is not correct. The correction effect is obvious, but there are great differences between different frequencies. The continuous revision for FE model is required.

6.3 The correction of structure parameter

As the bridge is a concrete bridge, as for Young's modulus and Density of concrete, the axial stiffness of main cable and suspenders, they are valued in accordance with the design value in theoretical calculation. But, there may be deviation in construction. As For the initial strain of main cable, it is not measured by environment vibration measurement in theory calculation. But, it is measured under the condition of the minimal internal force and the minimal deflection of girder under the load effect of FE model [8]. However, it is not practical. Therefore, modification on these parameters is required. It mainly focus on the analysis that the sensitivity response of the parameters of the FE model to natural vibration frequency of structure as well as the variation of objective function when parameter variation increased 3%. The sensitivity response of various parameters to the natural vibration frequency is shown in Figure 6.

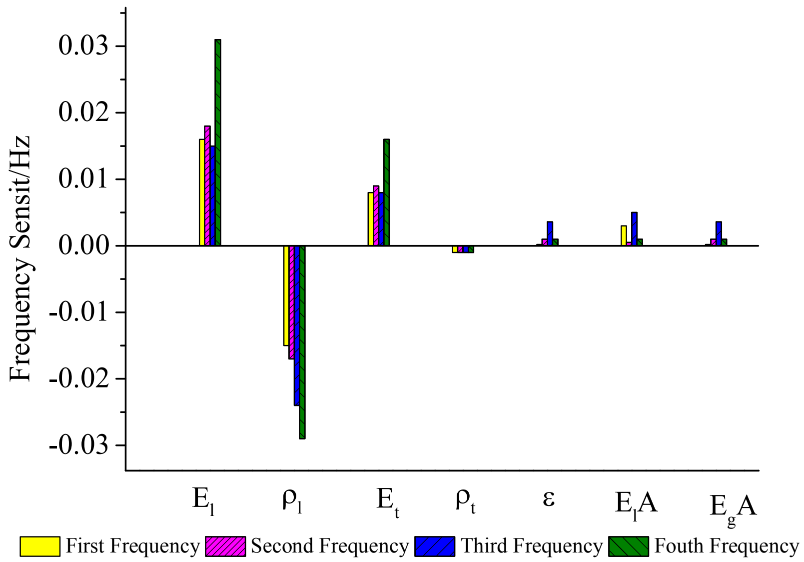


Figure 6 : The sensitivity response of various parameters to the natural vibration frequency

It can be seen from Figure 6, the Young's modulus and Density of main girder, Young's modulus of main tower have great impact on the natural frequency of vibration of structure. However, Density of main tower, initial strain of main cable, and axial stiffness of the main cable and suspender have small influence on the natural frequency of vibration. In particular, Young's modulus of main girder and Density of main girder have similar influence on structure of each order frequency.

6.4 the revised results

The revised structure parameters (shown in Table 4) and the contrast of calculated rate and the measured frequency values(shown in Table 5), which are calculated by using FE software ANSYS and adjusted the revised frequency for many times after it is calculated.

Corrected section	Structure parameter	Initial estimated value	Revised values
Girder	Young's modulus E_l	3.45×1010Pa	3.45×1010Pa
	Density ρ	2600 kg/m3	2990 kg/m3
Main tower	Young's modulus E_t	3.45×1010Pa	3.35×1010Pa
	Density ρ	2600 kg/m3	2600 kg/m3
Main cable	Initial strain ε	0.00128 ε	0.00124 ε
	Axial stiffness $E_l A$	1808605.5KN	1669482KN
Suspender	Axial stiffness $E_g A$	84328KN	80111.6KN

Table 4 : The revised of parameter values

Modal order	Measured frequency/Hz	Calculated frequency /Hz	Deviation/%	the Model of vibration
1	1.025	1.069	4.29	the First antisymmetric lateral bending girder
2	1.267	1.256	-0.87	the Second antisymmetric lateral bending girder
3	1.697	1.628	-4.07	the Third antisymmetric lateral bending girder
4	2.12	2.089	-1.46	the Forth antisymmetric lateral bending girder

Table 5 : Comparison on measured frequency and calculation frequency after the parameters is revised

According to Table 4, Density of girder, Young's modulus of main tower, initial strain and axial stiffness of main cable, and the axial stiffness of suspender are modified. According to Table 5, compared the revised structure parameters with the parameters before it is revised, the natural frequency of vibration of structure is closer to measured values. However, the vibration mode is not changed, which proves that the revised parameters are closer to the actual condition of the bridge. There are still deviation caused by variation of the environmental conditions in the process of the test and outside interference in the process of data acquisition.

7 CONCLUSION

Based on a being-used suspension footbridge, its dynamic characteristic is tested. And then, the parameter sensitivity analysis and modification of the model are made on its structure according to the test results and the structure calculation error. The revised model for dynamic characteristics calculation is close to the measured values. It provides more accurate FE model for the analysis and fully understanding the structure of dynamic properties and structural condition assessment.

REFERENCE:

[1] Pimentel R.l.,Pavic A.and Waldrom P..Evaluation of design requirements for footbridge excited by vertical forces from walking . Canadian Journal of Civil Engineering, 2001,28:769-777.

[2] C. Gentile *, N.Gallino. Ambient vibration testing and structural evaluation of an historic suspension footbridge . Advances in Engineering Software, 2008;(39): 356–366

[3] ZHANG Hong-bin, KONG Hong-bin, ZHANG Zhe. Research on Dynamic Performance of Self-anchored Suspension Bridge. Journal of Highway and Transportation Research and Development, 2004(21):66-69.

[4] Wang Xin-min, The Ansys Engineering Numerical Analysis, Beijing, China Communications Press,2011.

[5] YANG Yong-qin, CHEN Ai-rong, XIANG Hai-fang. Problems of Nodal Rigid Zone In Modeling Bridge Structures for Dynamic Analysis. China Civil Engineering Journal, 2001 (34) : 14 – 18.

[6] XU Jun-lan , XIANG Zhong-fu. Discussing Gravity Stiffness of Suspension Bridge, Journal of Chongqing Jiao Tong Institute, 2009(19):71—74.

[7] FAN Li-chu, YUAN Wan-cheng, ZHANG Qi-wei. Sensitivity-based FE Modal Updating of A Suspension Bridge . China Civil Engineering Journal, 2000(33) : 9– 13.

[8] WANG Chun-miao. Dynamic Performance Analysis of Runyang Suspension Bridge Using Ambient Vibration Measurement. Journal of Highway and Transportation Research and Development, 2006(23):56-59.