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EXPERIMENTAL VALIDATIONS OF MODEL UPDATING BASED ON MULTI-RESPONSE OBJECTION FUNCTION FOR CABLE-STAYED BRIDGES

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ABSTRACT

A multi-response objective function based method for model updating of cable-stayed bridge is experimentally validated in this paper. Finite element model updating by using of the measured data has become a promising way for evaluating the structural state of long span bridges. In general, modal data are commonly adopted for model updating in the existing studies. However, the cables are the critical structural members for the cable-stayed bridges. The cable forces play an important role of the static behavior of the bridge. Thus an accurate FE model is supposed to reflect the behavior of the real structure in both static and dynamic aspects, especially for cable-stayed bridges. A multi-response objective function based method was proposed for model updating in this study. The methodology presented here integrates the modal data with the static data, which has the advantage of considering the effect of static deflection on the modal parameters for cable-stayed bridges. Feasibility of the proposed approach is validated through an experimental program. The work involved development of a scale model of a cable-stayed bridge based on the elastic similitude law. A 1/150 scale-model of the cable-stayed Shengli Bridge was then built in the laboratory. An FE model of the bridge model was also established. The bridge model was subjected to both static and modal tests, and the experimental data were used to update the parameters of the FE model. The updating of the material parameters, as well as the cable forces, of the scaled model was performed, and the updated results were validated by the experimental measurements. Moreover, the prediction performance of the updated model was also investigated by modifying the structural configuration with loosing the cables. The results demonstrate that the proposed method can accurately update the structural parameters and predict the structural responses of the scaled model bridge. It is indicated that the presented approach has potential for diagnosing structural health and assessing the safety of cable-stayed bridges.

KEYWORDS

Finite element model updating, multi-response objective function, modal data, cable force, cable-stayed bridge.

INTRODUCTION

Finite element (FE) model updating, which belongs to the class of optimization problem (Teughels and De Roeck 2005), minimizes the differences between the experimental modal data and the corresponding analytical predictions through updating the parameters of FE model. In recent decades, the finite element model has become increasingly important for predicting both the dynamic and static responses of structures in civil engineering. It is an indispensable way for assessing the condition or monitoring the structural health of bridges by using an FE model combined with field load tests. However, in general, the initial FE model may not truly represent all the physical aspects of the structure, and the FE analytical results may differ from the measured results because of model structural errors, model parameter errors, and model order errors (Mottershead and Friswell 1993). It is necessary to improve the reliability of the FE model for prediction of the dynamic characteristics and responses to loads; thus, methods for refining the FE model have been introduced.

In this study, a novel multi-response objective function was proposed to update the finite element model for cable-stayed bridge and the iterative method was adopted with the aim of investigating the relationship between the physical model and FE model. However, studies on the verification of the FE model updating rarely appear in the literature. Therefore, it is of great interest to establish a physical model to testify the effectiveness of the FE model updating method. The test program involved both static and modal tests, and the experimental data were used to study the behavior of the cable-stayed bridge. A comparative study was also performed to demonstrate the effectiveness of the proposed methods. Finally, the responses of the updated FE model were compared with those from the model tests.

THE PHYSICAL MODEL OF SHENGLI BRIDGE

Shengli Bridge, with a total length of 2817.46m, was built in 1987 over the Yellow-river in China. The main bridge is a half-floating, cable-stayed bridge which includes five spans. The bridge is 19.5m in width and has four traffic lanes. The main cable-stayed superstructure consists of asphalt layer, railings and steel deck supported by two thin-wall box girders. The main bridge has two H-shape concrete pylons with the height of 69.7m above the pile cap. The pylon is divided into three sections by the beam. The middle section, which has variable cross sections, is made to be hollow above the deck for inspecting convenience. A total of eighty eight steel stay cables are in a fan arrangement with one end anchored at the box girder and the other end anchored at the upper sections of the H-shaped pylon.

The small-scale model of Shengli bridge was built in the laboratory based on similarity theory. The total length of the bridge was 4.55m, according to the linear scale factor (Caetano *et al.* 2000). The other similarity parameters were derived based on the similarity theory. The choice of such a small scale mainly depended on the dimensions of the testing field, which was not big enough to carry out both static and modal test. The box girder and the pylons, which were constructed in an aluminum alloy, were simulated with solid rectangular cross-sections with correctly scaled bending stiffness (both Y and Z axis in the plane) and torsion stiffness. Table 1 shows the scale factor of each designation. The cables were modeled by piano strings with correctly scaled axial stiffness. As for the boundary condition, the bottoms of the piers were fixed at a reinforced concrete block which was used as the foundation of the bridge on the shaking table for dynamic test. Nevertheless, the expansion joints at both ends of the bridge were not modeled.

According to the similarity theory, the deck of the physical model were attached a total of 112kg lead additional masses along the bridge axis to model the actual self-weight. Moreover, the lead sheets of different additional masses were also attached to the cables to satisfy similarity. However, it was hardly to implement the pylon's additional masses due to not enough space. One end of the cable was fixed at the top of the upper pylon, while the other end was wrapped into the bolts, by tuning which to change the cable force. Fig.1 shows the overview of the physical model bridge.

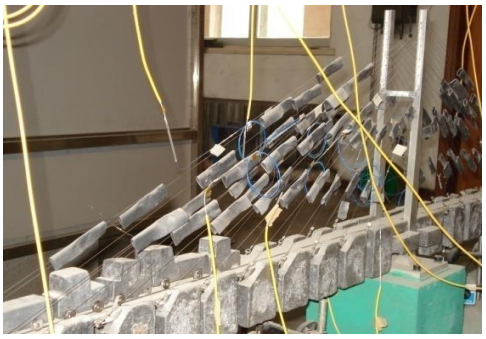

Figure 1. Overview of the bridge model

MODEL UPDATING METHOD

The critical step of model updating depends on how to select the objective function and the updated parameters properly. The objective function is an index of discrepancy between the FE analysis results and the measurements. Many researchers formulate the objective function in different types. Zhang *et al.* brought up an eigenvalue based function to update Kap Shui Mun cable-stayed bridge (2001); Hendrik Schlune *et al.* compared four general objective functions for FE model updating and applied them to a real bridge (2009); Bijaya Jaishi and Wei-Xin Ren illustrated a multiobjective function based on eigenvalue and strain energy (2007); Bijaya Jaishi *et al.* used modal flexibility to construct the objective function and successfully applied the method in a concrete-filled steel tubular bridge (2007). It is noted herein that the bridges that have the different cable forces and deflections might produce the same modal properties. Thus the FE model updating, which only adopts the dynamic measurements, might be unable to predict the cable forces and defections of the bridge in some cases The FE model in this study is aimed at representing the changes in cable force, deflections of the bridge deck, as well as the dynamic characteristics, when the bridge is subjected to the same static loads. In this study, a multi-response objective function is constructed as to reflect the responses of the bridge comprehensively. Both static and dynamic responses are taken into account, with deflections, frequencies and mode shapes chosen as each of the objective function item. When different types of measurements contribute to the objective function, it is important that they are unit-less. Normalization is therefore required to assure that the contribution to the objective function is not dependent on the units chosen. The objective function is defined

in Eq. (1):

$$J = \sum_{i=1}^{m_f} \left(\frac{f_{ei} - f_{ai}}{f_{ai}}\right)^2 + \sum_{j=1}^{m_s} \sum_{dof} \left(\frac{\phi_{aj}^l}{\phi_{aj}^r} - \frac{\phi_{ej}^l}{\phi_{ej}^r}\right)^2 + \sum_{k=1}^{s} \left(\frac{d_{ek} - d_{ak}}{d_{ak}}\right)^2 \quad (1)$$

where J is the objective function; f_{ei} and f_{ai} are the ith experimental and analytical frequency, respectively; ϕ_{ej} and ϕ_{aj} are the jth experimental and analytical mode shape component, respectively; The indices l and r of ϕ_j denote respectively an arbitrary and a reference degree of freedom of the mode shape; $\sum_{dof}$ denotes all the measuring DOF(degree of freedom); d_{ek} and d_{ak} are the experimental and analytical deflection of the kth measuring point respectively; m_f and m_s denote the number of the frequency and mode shape, respectively. s is the number of deflection measuring points. The main reason why the newly constructed objective function accounts for the deflection residual terms is that the improved accuracy for dynamic responses does not lead to an improved accuracy for static analysis. Therefore, static responses are taken into account to represent the static behavior of the cable-stayed bridge. There is an interaction effect between the cable forces and deflections, which are the two key responses to examine when determining whether the FE model can accurately model the static behavior of the cable-stayed bridge.

To accomplish this optimization task, the first order and sub-problem optimization method are used in this paper with ANSYS software. The methodology is applied to a physical model in the laboratory and its FE model and verification of the method are presented in the following sections.

In order to acquire the static responses of the bridge, a static loading test was carried out by applying truck loads on the middle span of the bridge. The truck loads were divided into two groups (A: 0.6 kg, B: 1.0 kg), weighing 8.8 kg in total, and were arranged in sequence as shown in Figure 2. The deflections of measuring points and the cable force changes were obtained after the truck loads were applied. A total of 11 dial test indicators were placed at different locations, with the numbering 1–11 from north to south.

Because the diameter of the cable was less than 1 mm and it was difficult to monitor the cable force change during the static loading test, we especially designed a gripper-based fiber Bragg grating (FBG) sensor with enhanced strain sensitivity to overcome these challenges. Twenty-four out of eighty-eight stay cables were connected to the FBG sensor. The FBG sensor demodulation device is shown in Figure 3.

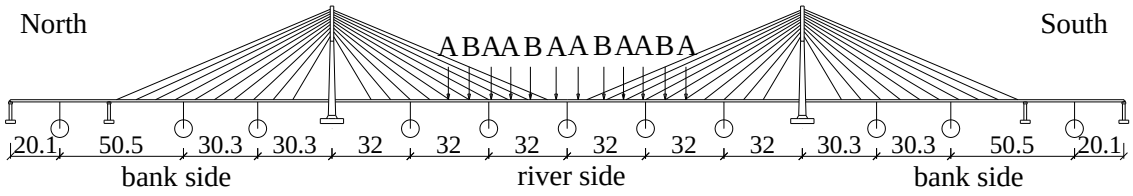

Figure 2. Location of the load and instrumentation (cm)

MODAL TESTS

The modal test was carried out in the laboratory, and the frequencies and mode shapes of the model bridge were obtained by using the peak picking method. Accelerometers were installed on the middle of the deck to measure the vibration responses in the vertical direction. SD1406 piezoelectric acceleration transducers were used to measure the vibration signals, which were collected by a telemetry data recorder (TDR) and analyzed with dynamic data processing (DDP) software. Figure 4 shows the deployment of the accelerometers.

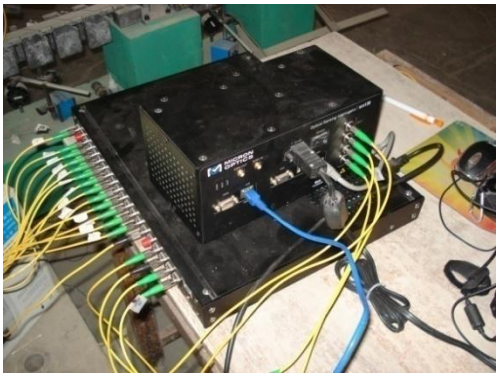

Figure 3. FBG sensor demodulation device

Figure 4. Deployment of accelerometers

A three-dimensional FE model was established as an initial model by using ANSYS software, which was expected to predict the results of the model test and instruct the operator to adjust the scale model in time. The entire model updating process was based on this FE model, and the geometric dimensions of the FE model were set strictly according to the blueprints of the scale model. This FE model was composed of four element types, as explained next. The deck was simulated with the Shell 63 element; the cables were simulated with the Link 10 element, which was a tension-only truss element; the pylon, pier, and the girder was simulated with the Beam 188 element; and the pile caps were simulated with the Solid 45 element. The connection where the solid element met the beam element was set as the rigid region. The transverse and vertical DOFs of the deck were constrained at the location of the pylon, and all the longitudinal DOFs were released. The bottom of the pile caps was fixed at the concrete block. A total of 1567 elements and 1184 nodes were used to establish the FE model. Figure 5 provides the general view of the FE model, and Fig. 11 shows the first three vertical bending mode shapes.

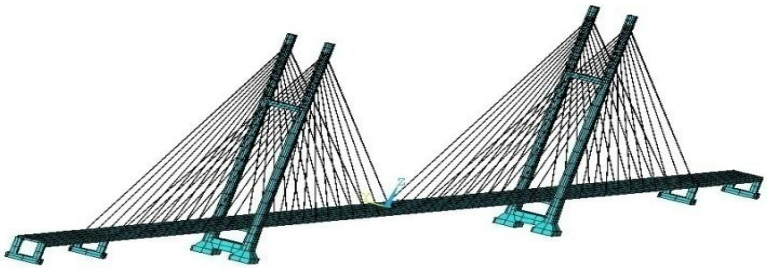

Figure 5. FE model of the bridge

The advantages of FE model updating are that it can not only exclude several factors that may influence the updating problem, e.g., the boundary condition of the bridge model has been much simplified, but also improve the accuracy of measurements and reduce costs. The selection of parameters is also very important in the process of model updating. To avoid the ill-conditioned problem of the optimization, the number of selected parameters needs to be reduced. In general, sensitivity analysis is carried out to help identify the parameters that are most sensitive to the response of the structure. Hence, the density and Young's modulus of the bridge deck, the thickness of the bridge deck, as well as the height and width of the girder were chosen as the updated parameters. In fact, the density of the deck with added masses can be computed as the equivalent density defined in Eq. (2), which will be used to verify the updating method.

$$\rho_{equ} = \frac{m_d + m_w}{V_d} \tag{2}$$

where m_d is the mass of the bridge deck, m_w is the mass of the added weights, and V_d is the volume of the bridge deck. The equivalent density is 12600kg/m^3.

Before updating, the initial Young's modulus of the deck was set as 50 GPa, and the initial density of the bridge deck was set as 15000 kg/m^3. The tolerances for the design variables, state variables, and objective function were all properly defined. First, the first-order method was used to solve the optimization problem, and then, the sub-problem method was used to verify the updating results that prevented the algorithm trap in local minima.

In this study, the deflection residuals were added to the objective function to enhance the accuracy of the updated FE model (referred to as FEM 1). In order to highlight the effectiveness of the proposed objective function, another objective function without the deflection residuals was formulated and used for model updating, which was referred to as FEM 2. The updated parameters are shown in Table 1. As can be seen in Table 1, the updated density of FEM 1 is very close to the equivalent density, which verified the effectiveness of the updating method. The first three vertical bending frequencies (f_1, f_2, and f_3) were also calculated with the two different updated models, and they were compared with the measured values in Table 2.

Table 1. Parameters for initial and updated models

Parameters	Initial model	Updated FEM1	Change (%)	Updated FEM2	Change (%)
Density (kg/m^3)	15000	12700	-15.3	14000	-6.67
Elastic modulus (Gpa)	50	83.6	67.2	62.2	34.4
Thickness of the deck (mm)	3.5	4.48	28	3.56	1.7
Height of the girder (mm)	5.7	6.54	14.7	8.12	42.5
Width of the girder (mm)	4.0	2.32	42	2.76	-31

Table 2. Comparison between computed and measured frequencies

Frequency	Experiment	FEM1 (Hz)	Change (%)	FEM2 (Hz)	Change (%)
f_1	6.32	6.61	4.59	6.61	4.59
f_2	10.08	9.69	-3.87	9.59	-4.86
f_3	15.00	13.71	-8.6	13.58	-9.47

The cable of a cable-stayed bridge is the most important structural member, and the cable force plays a critical role in the dynamic as well as the static responses of the bridge. Thus, updating of the cable force should be studied with two different objective functions. In the model tests, the truck loads were applied to the model and the changes in the cable forces were measured. Under the application of truck loads, the corresponding defections and modal responses were used to update the changes in the cable forces. The updated static responses are listed in Table 3 and Table 4 with two different objective functions. It can be seen that the errors in the updated cable force changes are all less than 10% for FEM 1, and the maximum error in predicting the deflection is less than 16%, which can meet the requirements of model updating for real applications. On the other hand, FEM 2 produces relatively large errors both in predicting the cable force change and deflections. Hence, it is demonstrated that the approach proposed in this paper (i.e., FEM 1) is able to update not only the cable force change but also the structural responses for the bridge model.

Table 3. Comparison between the measured and computed cable force changes

Location of the cable	Experiment (N)	FEM1 (N)	Error1 (%)	FEM2 (N)	Error2 (%)
b1	-0.71	-0.566	-20.28	-0.473	-33.38
b4	-0.5	-0.575	15.00	-0.658	31.60
b7	2.85	2.946	3.37	2.711	-4.88
b11	9.3	9.084	-2.32	9.29	-0.11
r1	-0.34	-0.312	-8.24	-0.364	7.06
r4	2.72	2.816	3.53	2.667	-1.95
r7	7.56	7.427	-1.76	7.501	-0.78
r11	6.73	6.356	-5.56	6.441	-4.29
b1'	-0.67	-0.566	-15.52	-0.473	-29.40
b11'	8.17	9.084	11.19	9.29	13.71
r1'	-0.31	-0.313	0.97	-0.364	17.42
r6'	7.26	6.476	-10.80	6.495	-10.54
r11'	5.8	6.356	9.59	6.44	11.03

Table 4. Comparison between the measured and computed deflections

Deflection measuring point	Experiment (mm)	FEM 1 (mm)	Error1 (%)	FEM 2 (mm)	Error2 (%)
1	-0.13	-0.14	10.27	-0.16	21.00
2	0.49	0.50	2.97	0.53	8.90
3	0.24	0.27	15.07	0.28	16.81
4	-0.39	-0.40	4.23	-0.41	5.12
5	-1.27	-1.22	-3.85	-1.25	-1.85
6	-1.72	-1.61	-6.15	-1.65	-3.94
7	-1.15	-1.22	6.06	-1.25	8.28
8	-0.43	-0.40	-7.29	-0.41	-6.49
9	0.32	0.27	-13.43	0.28	-12.11
10	0.57	0.50	-11.40	0.53	-6.30
11	-0.12	-0.14	13.48	-0.15	24.50

PREDICTIONS OF STRUCTURAL RESPONSES WITH THE PROPOSED APPROACH

A critical issue should be addressed. The purpose of model updating is to obtain an agreement between the numerical results and the measured data. As discussed in the last section, the identification performance of the proposed approach was validated by the model tests for both the material parameters and the structural responses. The prediction accuracy with the updated model was studied as follows.

In this study, the measured changes in the responses were used to calibrate the predicted changes calculated by

the updated FE model. These changes were induced by loosening a cable in the model bridge. The loose cable was used to simulate the variation in the cable force that is caused by corrosion or fatigue damage. Because the scale ratio of the model bridge is very small, it is very difficult to control the cable force quantitatively. Thus, we loosened the cable to simulate the changes caused by damage, which is a kind of the modification of the structural configuration. As a result, the structural responses of the bridge model also changed. To predict the changes, the corresponding cable was also loosened in the FE model (i.e., FEM 1). The calculated responses were subsequently compared with the measured responses.

In the experiments, two cables each (upstream and downstream) at locations b5 and b9 from the north span were loosened respectively when the middle span was loaded with the model trucks (total weight: 8.8 kg). Here, "b" denotes the cable that is close to the bank of the river, and the numerals "5" and "9" represent the 5th and 9th cables, respectively, from the north bank. When the cables were loosened in each case, the forces in each cable correspondingly changed and redistributed, and the deflections of the bridge deck also changed. Before and after the cables were loosened, the cable forces and the deflections of the model bridge were measured. The changes in the cable forces and in the deflections were then compared with those predicted by the structural analysis with FEM 1. The results are shown in Figures. 6–9. As can be seen from these figures, both the cable force changes and the deflection changes predicted by the FE model are in good agreement with those obtained by the model test. The proposed model updating method can precisely predict unknown structural behavior and has the potential to diagnose structural health and assess the safety of cable-stayed bridges.

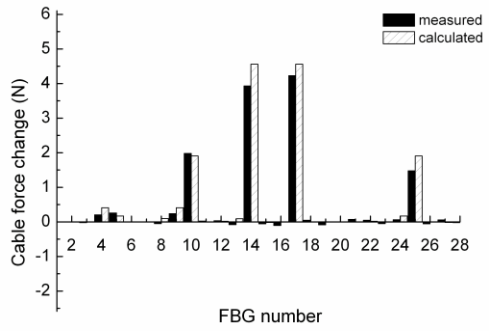

Figure 6. Cable force change when b5 were loosened

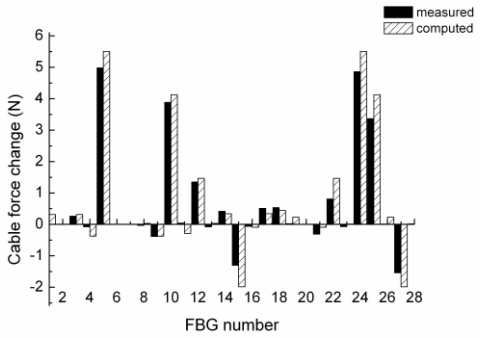

Figure 7. Cable force change when b9 were loosened

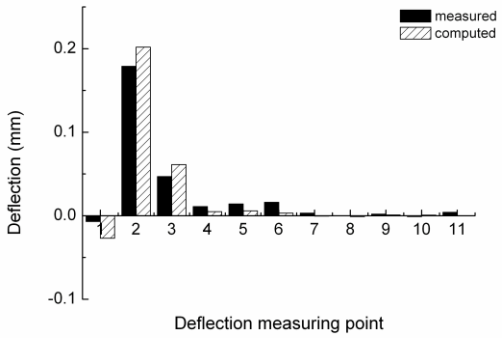

Figure 8. Deflection when b5 were loosened

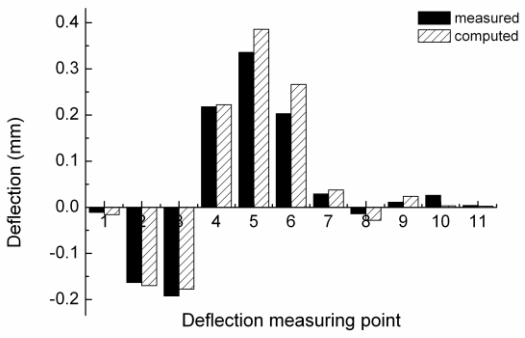

Figure 9. Deflections when cables at b9 were loosened

CONCLUSIONS

A multi-response objective function approach for updating of a cable-stayed bridge model was presented in this paper, and its effectiveness was experimentally investigated by a series of small-scale model tests. Evaluation of the proposed method was accomplished on a 1/150-scale cable-stayed bridge model in the laboratory with both static and modal tests. The results showed that (1) the updated parameters were in good agreement with the measured parameters of the bridge model; (2) the updated FE model can not only identify the material parameters as well as the cable forces of the bridge model, but it can also predict the structural responses with higher accuracy when the cable-stayed bridge is modified its structural configuration; and (3) the proposed

model updating approach is potentially useful for diagnosing structural health and assessing the safety of cable-stayed bridges.

ACKNOWLEDGMENTS

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