Engineering Structures 32 (2010) 2546–2556

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Progressive finite element model calibration of a long-span suspension bridge based on ambient vibration and static measurements

Hao Wang [a,b,*], Ai-qun Li [a], Jian Li [b]

[a] *College of Civil Engineering, Southeast University, Nanjing 210096, PR China*

[b] *Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*

ARTICLE INFO

Article history:
Received 9 December 2008
Received in revised form
21 April 2010
Accepted 22 April 2010
Available online 8 June 2010

Keywords:
Suspension bridge
Finite element (FE)
Model updating
Baseline model
Structural health monitoring

ABSTRACT

A two-phase model updating approach is presented to develop a baseline model for the Runyang Suspension Bridge (RSB), which is the longest bridge in China with a main span of 1490 m. In this approach, the model updating is divided into two phases of free-standing tower phase and full-bridge phase according to the construction procedure, so that the model updating of the long-span suspension bridge can be greatly simplified. The physical meaning of sensitivity and the penalty function concept is employed in the iterative calculation. The structural model is updated by modifying the parameters of design, and validated by structural natural vibration characteristics and static responses. The design parameters used for updating are bounded according to measured static results and engineering judgments. After ambient vibration measurements were carried out to obtain the eigenfrequencies, damping ratios and mode shapes of RSB based on the monitored acceleration records, the FE model is then updated by using the measurements come from field tests during construction of the bridge and after the completion of the bridge. The calibrated FE model is proved to have a good correlation with the static and dynamic measurements and is then used for the continuous structural health monitoring of the bridge.

1. Introduction

In recent decades, great development has been achieved in the design and construction of long-span suspension bridges in the world. For example, the Akashi Kaikyo Bridge with a main span of 1990 m in Japan and the Great Belt Bridge with a main span of 1624 m in Denmark. Until now, it is still the most competitive scheme of the bridges whose spans exceed 1000 m [1]. With the rapid increase of span, bridges are becoming lighter, slender and more sensitive to dynamic loads, and some new problems are arising. Therefore, to prevent potential catastrophic events happening on these important long-span suspension bridges, continuous health monitoring and regular condition assessment are necessary so that early identification and localization of any potential damage in the bridges can be made [2–5].

As we all know, the research basis for carrying out any kind of structural numerical analysis is to establish a baseline finite element (FE) model of the structure. An accurate and reliable FE model is indispensable for studies on structural health monitoring and condition assessment, wind-resistance and earthquake-resistance, vibration control, etc. Therefore, many scholars all over the world focus on FE model updating studies based on measurement data in order to achieve an FE baseline model suitable for the analysis object [6–11]. As a result, a number of model updating techniques have been proposed over the years in the fields of mechanical, aerospace and civil engineering for various purposes.

Typically, an FE model is modified in such a way that its dynamic behavior resembles, as closely as possible, that of the structure being analyzed. In most of the model updating approaches, the most probable dynamic properties of the structure are found by reducing the error between the measured response of the structure and the calculated response from a numerical model. Mass and stiffness matrices are updated using the measured dynamic properties.

Model updating is an inverse problem in which the structural parameters are desired by manipulating the information extracted from the observed behavior/data of the system. Due to this nature, the problem is inevitably ill-posed; otherwise the complete information of the behavior/data would be required which is impossible in reality [12]. One indication of the illness is the non-uniqueness of the solution. Only limited number of structural parameters can be defined due to the capability of the optimal search techniques and limited measurements are available; therefore, more than one combination of parameter values are always exist which can achieve more or less a comparable solution that can meet the criteria of "optimum". Consequently, a tradeoff between

---

* Corresponding author at: College of Civil Engineering, Southeast University, Nanjing 210096, PR China. Tel.: +86 25 83269996.
E-mail address: whzjn@sina.com (H. Wang).

0141-0296/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2010.04.028

the complexity and the accuracy of the numerical model has to be made. Furthermore, the accuracy of the solution strongly relies on the accuracy of the system identification results which are the input to the model updating problem, in that a tiny change of system property may significantly alter the finally achieved solution [12–15]. Therefore, a reliable and accurate system identification method is always desired for model updating.

Being aware of the above mentioned limitations of model updating technique, several countermeasures can be proposed to tackle them. Firstly, the dynamic information, including the natural frequencies and mode shapes are commonly and oftentimes exclusively used as the input into the model updating problems [16–18]. However, the static response of the structure is neglected. Consequently, significant error may still exit in the static response of the updated model. In this regard, adding the measured static information into the input of model updating problem would not only enrich the input information, but also guarantee the accuracy of the updated model in terms of both dynamic and static properties. Secondly, the capability of the optimal search techniques is always the bottleneck in the number of candidate parameters. To circumvent this limitation, a progressive model updating strategy which involves the rule of separate-and-conquer has the potential to allow more parameters to be updated, hence increase the fidelity of the updated model.

The Runyang suspension bridge (RSB) is taken as an example. The main motivation of this study is to establish the baseline FE model for continuous health monitoring of RSB, so that the static and dynamic responses can be predicted through the baseline model. To simplify the analysis and avoid too much updated parameters, a progressive model updating strategy is applied by dividing the updating procedure into two phases including the free-standing tower phase and the full-bridge phase according to the construction procedure. At the same time, a new approach of model updating with extended input information is developed based on the physical meaning of sensitivity. In this approach, the structural model is updated by modifying the design parameters, and validated by structural dynamic properties, stress and displacement response of the girder from field load tests and the structural health monitoring system (SHMS) of RSB [19]. It is expected the outcome of this study will be useful to researchers and professionals involved in complicated civil structures.

2. Bridge description

The RSB, as shown in Fig. 1, is one of the long-span bridges crossing the Yangtse River in Jiangsu Province, China. It is a single-span hinged and simply supported suspension bridge with a main span of 1490 m, as can be seen in Fig. 2. It is the longest suspension bridge in China and the third in the world. The width and height of the streamlined steel box girder is 36.3 m and 3.0 m, respectively. The two side spans are 470 m and there is no suspender in the side span, as shown in Fig. 2.

The full-joint streamline flat steel box girder is employed in the RSB and the full length of the main girder is 1485.16 m. The distance between the transverse clapboard in the steel box girder is 3.22 m. The three-story frame structure is applied in the two towers. There are two tower columns with three pre-stressed concrete crossbeams (top, middle and bottom crossbeams) in each tower. The rectangular single-box single-chamber structure with variable wall thickness is used in the tower column. The heights of the two towers are about 210 m. The group pile foundations are used and the bottoms of the piles are embedded in rock. The main cable is made up of the prefab parallel subsection cables. There are 127 high-strength steel wires in each subsection cable and each main cable contains 184 subsection cables. The distance between two adjacent suspenders is 16.1 m and the rigid central buckle is firstly used in suspension bridge in China [19].

Fig. 1. Runyang suspension bridge (RSB).

3. FE model and FE analysis

3.1. FE model

In the three-dimensional FE mode of RSB established by ANSYS [20], the deck, the central buckle and the towers were simulated by beam elements (BEAM4) with six degrees of freedom (DOFs) for each node. As a traditional deck spine model, the suspenders and the deck were linked with massless rigid elements placed perpendicular to the spine. The main cables and the suspenders were simulated by three-dimensional linear elastic truss elements (LINK10) with three DOFs for each node. The main cables and the deck were meshed according to the nodes of the suspenders. The pavement and the railings on the steel box girder were simulated by mass elements (MASS21) without rigidity. The nonlinear stiffness characteristic of the back cables due to gravity effect was approximately simulated by linearizing the cable stiffness using the Ernst equation of equivalent modulus of elasticity [21].

The deck and the corresponding crossbeams of the towers were coupled in three DOFs including vertical displacement (UY), lateral displacement (UZ) and rotation around longitudinal direction (ROTX). The central buckle was precisely simulated and coupled with the deck and the main cables according to the design. According to the design of the main cable saddle in RSB, the main cable could be stably clamped by the main cable saddle installed on the top of the tower, hence there is no relative displacement between the main cable and the main tower after the bridge is finished and open to the traffic. Therefore, the main cables are fixed on the top of the towers. The research results in Ref. [22] show that the effects of soil–pile-structure interaction on the dynamic behavior of RSB are negligible, so the bottom of both the back cables and the towers are fixed at the bases.

3.2. Two-phase FE analysis

The long-span suspension bridge is a flexible structure and the gravity rigidity caused by dead load is of great significance; therefore, the geometric nonlinearity must be considered. In order to obtain the frequencies and mode shapes of RSB, the Pre-stressed Modal Analysis module in ANSYS is employed and the modal analysis is performed following a nonlinear static analysis with large deflection, by which the internal forces caused by the dead loads acting on the bridge was obtained. The stress stiffening matrix caused by the internal forces was incorporated to formulate the updated tangent stiffness matrix. Then the modal analysis was performed on basis of the deformed equilibrium configuration obtained by considering the effect of the dead loads acting on the bridge. As a result, the natural frequencies and vibration modes