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Baseline finite element modeling of a large span cable-stayed bridge through field ambient vibration tests

Wei-Xin Ren [a,b,*], Xue-Lin Peng [a]

[a] *Department of Civil Engineering, Fuzhou University, Fuzhou, Fujian Province 350002, PR China*
[b] *Department of Civil Engineering, Central South University, Changsha, Hunan Province 410075, PR China*

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Abstract

A baseline finite element model is a reference in structural damage detection and long-term health monitoring. An ambient vibration measurement based procedure is presented to develop such a baseline model for a newly constructed Qingzhou cable-stayed bridge over the Ming River, Fuzhou, China. A 605 m main span of the bridge is currently the longest in the world among all completed composite-deck cable-stayed bridges. The procedure includes several tasks: finite element modeling, field ambient vibration testing, parametric studies and model validation. It is demonstrated that the ambient vibration measurements are enough to identify the most significant modes of large span cable-stayed bridges with a low range (0–1.0 Hz) of natural frequencies of interest. Some important issues in the modeling of such a complicated bridge, such as the initial equilibrium configuration due to dead load, geometrical nonlinearities, concrete slab, the shear connection of the composite deck, and the longitudinal restraints of the end expansion joints, have been clarified. The developed three-dimensional finite element model of the bridge has achieved a good correlation with the measured natural frequencies and mode shapes identified from field ambient vibration tests.

Keywords: Cable-stayed bridge; Finite element model; Baseline; Structural dynamics; Health monitoring; Ambient vibration test; Modal analysis; Cable tension

1. Introduction

Civil infrastructures serve as the underpinnings of our present highly industrialized society. It is an important issue how to monitor these widely used infrastructures in order to prevent potential catastrophic events. Bridges, a type of important civil infrastructures, are normally designed to have long life span. Service loads, environmental and accidental actions may cause damage to bridges. Continuous health monitoring or regular condition assessment of important bridges is necessary so that early identification and localization of any potential damage can be made.

The contemporary cable-stayed bridge is becoming more and more popular and being used where previously a suspension bridge might have been chosen. The increasing popularity of cable-stayed bridges are

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[*] Corresponding author. Address: Department of Civil Engineering, Fuzhou University, Fuzhou, Fujian Province 350002, PR China. Tel.: +86 591 87892454; fax: +86 591 83737442.

E-mail address: ren@fzu.edu.cn (W.-X. Ren).

URL: http://bridge.fzu.edu.cn.

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attributed to, (1) the appealing aesthetics; (2) the full and efficient utilization of structural materials; (3) the increased stiffness over suspension bridges; and (4) the relatively small size of the bridge elements. Very large spans have been built, for examples, 890 m for Tartara bridge in Japan, 856 m for Pont de Normandie bridge in France, and 628 m for Nancha bridge in China. Cable-stayed bridges are now entering into new era, increasing a central span length to 1000 m or even longer.

There have been several concerns over the use of cable-stayed bridges despite all the advantages. Cable-stayed bridges are apt to look somewhat angular and highly stressed. They are normally sensitive to dynamic loadings such as earthquakes, winds and vehicles. Moreover, the health monitoring and condition assessment of large span cable-stayed bridges is a crucial issue to ensure safety during the bridge service life. One way to carry out the health monitoring or structural assessment is through changes in vibration characteristics (natural frequencies, damping ratios, and mode shapes) of bridges. Those changes, if properly identified and classified, can provide the means for assessing the damage of the structure [1].

Due to the structural complexity of large span cable-stayed bridges, the finite element (FE) method is currently a common way to perform the modal analysis and dynamic response analysis under earthquake, wind and vehicle loadings [2–9]. Starting from the knowledge of the structure geometry, the boundary conditions and material properties, the mass, stiffness and damping distribution of the structure are expressed in a matrix form. To identify changes in the dynamic characteristics of a bridge, a baseline finite element is often required. Bridge health can be monitored or assessed when the baseline model is compared against a finite element model of the updated bridge. However, the success of finite element method application strongly depends on the reliability of the model since many simplifying assumptions are made in modeling the complicated structures, and there are many uncertainties in the material and geometric properties. The calculated results are often questionable if the finite element model is not properly validated by the field test results.

Field dynamic testing of a bridge provides a direct way to estimate its dynamic characteristics. There are three main types of bridge dynamic tests: (1) forced vibration tests; (2) free vibration tests; and (3) ambient vibration tests. In the forced vibration method, the bridge is excited by artificial means and correlated input–output measurements are performed. In the case of large and flexible bridges, like cable-stayed bridges, it often requires very heavy equipment and involves significant resources to provide controlled excitation at sufficiently high levels [10], which becomes difficult and costly. Free vibration tests of bridges is carried out by a sudden release of a heavy load or mass appropriately connected to the bridge deck [11]. Both forced and free vibration tests, however, need an artificial means to excite the bridge, additionally traffic has to be shut down during the tests.

Ambient vibration tests have an advantage of being inexpensive since no equipment is needed to excite the bridge. It corresponds to the real operating condition of the bridge. The service state need not have to be interrupted to use this technique. Ambient vibration tests have been successfully applied to several large scale cable-supported bridges [12–19]. In case of ambient vibration tests, only response data are measured while actual loading conditions are not measured. A modal parameter identification procedure will therefore need to base itself on output-only data.

In the first effort to carry out the long-term health monitoring on the Qingzhou cable-stayed bridge that was newly constructed in Fuzhou, China, this study is aimed at presenting an ambient vibration based procedure to establish a baseline finite element model of the bridge. An initial full three-dimensional finite element model of the Qingzhou cable-stayed bridge is first conceived according to the original blue prints. The field ambient vibration tests were carried out just prior to opening the bridge. Two complementary modal parameter identification techniques are implemented to obtain the basic dynamic characteristics of the bridge. They are rather simple peak picking (PP) method in frequency-domain and more advanced stochastic subspace identification (SSI) method in time-domain. The initial finite element model is then verified with the field test results in terms of frequencies and mode shapes. Some important issues in the modeling of such a complicated bridge have been clarified, such as the initial equilibrium configuration due to dead load, geometrical nonlinearities, concrete slab, the shear connection of composite deck, and the longitudinal restraints of end expansion joints. The experimentally verified finite element model can be used as a baseline for the dynamic health monitoring and succeeding dynamic response analysis of the bridge.

2. Bridge description

The Qingzhou cable-stayed bridge, as shown in Fig. 1, is one of the bridges on Luo-Chang Highway over the Ming River in Fuzhou, Fujian Province, China. The bridge has a composite-deck system consisting of five spans with an overall length of 1186.34 m (41.13 m + 250 m + 605 m + 250 m + 40.21 m). Its 605 m main span is currently the longest span length among the completed composite-deck cable-stayed bridges, and ranks the fifth among the all types completed cable-stayed bridges all over the world. The bridge was completed in the year of 2000, but it was officially