Journal of Constructional Steel Research 101 (2014) 385–394

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Analytical and experimental dynamic behavior of a new type of cable-arch bridge

H.J. Kang [a,b,*], Y.Y. Zhao [a], H.P. Zhu [b]

[a] College of Civil Engineering, Hunan University, Changsha 410082, China
[b] School of Computing, Engineering and Mathematics, University of Western Sydney, Locked Bag 1797, Penrith, NSW 2751, Australia

ARTICLE INFO

Article history:
Received 18 July 2013
Accepted 8 June 2014
Available online 30 June 2014

Keywords:
Composite bridge
Finite element method
Modal test
Identification

ABSTRACT

It is meaningful and significant to develop a new type of arch-based bridge in order to improve the competitiveness and promote the development of arch bridge. In this work, the laboratory testing and finite element methods are used to study the dynamic behavior of a model cable-arch bridge with a total length of 25.6 m. The validation of the applicability of the finite element method in this study is conducted by comparing with experiment in terms of mode shape and frequency and with ambient test according to the similarity relation. The effects of number and initial tension force of cable on the dynamic behavior of the model bridge are examined by using the testing method, while the effects of oblique angle of main arch, wind bearing and stringer's stiffness are analyzed in detail using the analytical method. The results indicate that the cable-arch bridge has a better dynamic behavior in lower vertical and torsional modes than pure arch bridges, which would be beneficial to the main span enlargement of cable-arch bridges.

1. Introduction

Arch bridge is a very common bridge, and long-span arch bridge over deep valleys has no competitors as far as aesthetics is concerned. However, recently, pure arch bridge is losing its advantage in large span bridge construction due to its limitation in the increase of length of arch span. In fact, the main span length of other types of bridges has reached a new record, for example, Akashi Kaikyo Bridge (a suspension bridge in Japan) with a span of 1991 m [1] and Sutong Bridge (a cable-stayed bridge in China) with a span of 1088 m [2], comparing with the longest span of 552 m for arch bridge [3]. It is difficult to further increase the length of an arch span because rise-span ratio would become smaller and arch may become instable under loads when arch span becomes longer. Thus, to regain the competitiveness of arch structure bridge, the development of new types of composite bridges with arch structure is becoming increasingly important. Recently, some new composite bridges have been founded or proposed and demonstrated to exhibit some better mechanical behaviors [4–6]. In these bridges, the stay cables are not anchored on their arches but their decks. Therefore, strictly speaking, they are not real cable-stayed arch bridges (cable-arch bridges). According to our knowledge, the only real cable-arch bridge was completed in China in 2007, in which the lower end of the inclined cable is anchored on the arch rib and the upper end on the pylon [7]. The static behavior of this new type of bridge was investigated in our previous work [8]. Understanding the dynamic behavior of such a bridge is very important for its development, but there has been a limited attention to date to this aspect.

In this work, we study the dynamic behavior of a cable-arch bridge. The modal test and analytical research on the dynamic behavior of the bridge, including the natural frequency and mode shape, are carried out on the basis of a small actual model bridge and an analytical finite element model. The model bridge is designed according to a reduced scale of 1/25, with a real prototype bridge with a 640 m span. Generally, the finite element method is currently a common way to perform a theoretical modal analysis of a new structure. However, some uncertainties are always associated with establishing an accurate finite element model. Hence, even if we are entering the age of virtual prototyping, experimental modal analysis (EMA) still plays a key role. It helps the structural dynamicist to reconcile numerical predictions with experimental investigations. Actually, model test and FE model analysis have been widely used to study the mechanical behavior of structures [9–11].

In bridge's modal tests, there are many techniques for ambient vibration system identification, such as the single-degree-of-freedom identification method [12,13], peak picking from the power spectral densities [14], the natural excitation technique [15] and stochastic subspace identification [16]. The modal identification techniques for controlled laboratory tests have been relatively mature [17]. In the present work, the experimental modal analysis procedure is carried out according to both input and output measurement data through the frequency response functions in the frequency domain, or impulse response functions in the time domain. The circle-fitting method

* Corresponding author at: College of Civil Engineering, Hunan University, Lushan South Road, No. 1, Changsha 410082, China. Tel.: +86 731 88822722.
E-mail address: khjun@hnu.edu.cn (H.J. Kang).

http://dx.doi.org/10.1016/j.jcsr.2014.06.005
0143-974X/

(CFM) [17] and Eigensystem Realization Algorithm (ERA) [18] are used to identify the modal parameters.

The structure of this paper is outlined as follows. A model cable-arch bridge is designed and illustrated in detail in Section 2. A three-dimensional finite element model is constructed using ANSYS in Section 3. The testing procedure and modal identification techniques are introduced in Section 4. The experimental and analytical modal analysis of the model cable-arch bridge are carried out and discussed in Section 5. The comparison between the two methods and the site test is carried out in terms of the mode shape and frequency of the bridge. The sensitivity of some key parameters on the dynamic behaviors of the cable-arch bridge is analyzed in detail using the experimental or analytical method.

2. A model cable-arch bridge

In order to evaluate the dynamical performance of the new type of cable-arch bridge and provide some beneficial design recommendations, a scaled model cable-arch bridge was constructed and tested based on a real bridge. The similarity theory and principle has been used in the design of the model bridge. The scale ratio S_L of the model bridge to the prototype is 1:25, namely $S_L = 1/25$. The majority of the geometric dimensions were designed according to the scale ratio and only some small components, which could not be found due to the fact of manufacture, were not strictly designed according to the scale ratio. In order to overcome the shortcoming, the sensitivity of such components and their dimensions and materials to the dynamic behavior of the bridge were carried out and the equivalent stiffness was also used to solve the problem. In the design, the boundary conditions of the model bridge are also similar to those of the prototype. Some specific similarity relations will be presented in Section 5. Additionally, in this work the emphasis is placed to investigate the dynamic behavior of cable-arch bridge and the stiffness of stringers is weakened and decreased to 10% in order to highlight the role of cable-arch structure. The model cable-arch bridge considered here (Fig. 1a) is the same as the one in our previous study [8]. The structure members are made of Q345 steel except the abutments, cushion caps and collar beams of the abutments, which are made of C50 concrete. The main structure and dimensions of the model bridge are as follows.

The structure is a combination of arch bridge and two-pylon cable stayed bridge. The deck below the main arches is supported by arch hangers and the rest of the main span by stay cables. The deck of the two side spans is supported by stay cables and side arches. The main span is 16 m and two side spans are 4.8 m each. The vase shaped pylons are 3.458 m high and 2.74 m tall above the deck. Fig. 2 shows the layout of bridge structure and measured points.

The cable-arch model bridge is also a half-through arch bridge and the double-rib higher parabolic hingless arches are adopted. The vault of the main arches is 2.988 m high totally and 2.15 m high above the deck. From the foot to vault, the depth of the main arches varies from 0.2 to 0.36 m, and the distance between the center lines of the two parallel arches is 1.36 m. Each main arch rib is space truss and the cross section consists of six steel tubes (see Fig. 3) with the dimensions of $\Phi 34 \times 2.5$ (2, 1) mm and connecting steel pipes. The two parallel main arch ribs are stabilized by 11 wind bracings, two K-shaped wind bracings and two connecting beams below the deck, and six K-shaped wind bracings and one Ж-shaped wind bracing above. The connecting beams are composed of the rectangle steel girders and other wind bracings are made of steel pipes.

The main arch floor system is composed of deck, I-shaped cross girder and longitudinal stringer. The rest consists of two longitudinal box girders. There are four expansion joints on the bridge deck. Two of them are between approach span and side span, and the others are between main span and side span.

The pylons are vertical in the longitudinal direction and vase-shape in the lateral direction as shown in Fig. 1a. The tower legs are hollow rectangle steel box and connected by three hollow steel box struts, two above the deck and one below, which simply supports the deck. The 56 cables are anchored at an 80 mm interval on the upper segments of each pylon.

To suspend the main arch floor system, there are 39 steel wire rope hangers with the dimension of Φ7 at each main arch rib. There are in total $28 \times 4 = 112$ stay cables with the dimension of Φ6.2. Some stay cables are anchored at a 400 mm interval on deck and others at a 320 mm horizontal interval on the arch rib. It is worth noting that there are two parallel cables anchored on the same cross-section of a main arch rib as shown in Fig. 3.

The main arch foot, pylon socket and the side arch foot are supported on the same piled foundation with 24 bore $\Phi 80 \times 5$ piles as shown in Fig. 2. The main arch rib and side arch rib, which is lower parabolic hingeless arch with the hollow rectangle steel box cross section, are fixed at abutment to balance the horizontal forces. As tie bars, four pre-stressed cables are used to connect the upper ends of the two side arches. Each cable is pre-stressed by 14.8 kN force and composed of 7 strands with a diameter of Φ5.

3. 3D finite element model

In order to model this cable-arch bridge, the finite element analysis software ANSYS 10 for Windows has been used. Fig. 1b shows the full 3-D view of the FE model of the cable-arch model bridge. The truss arch members, bracing members, towers, side beams, side arch members and piles are represented as two-node beam elements (BEAM44)

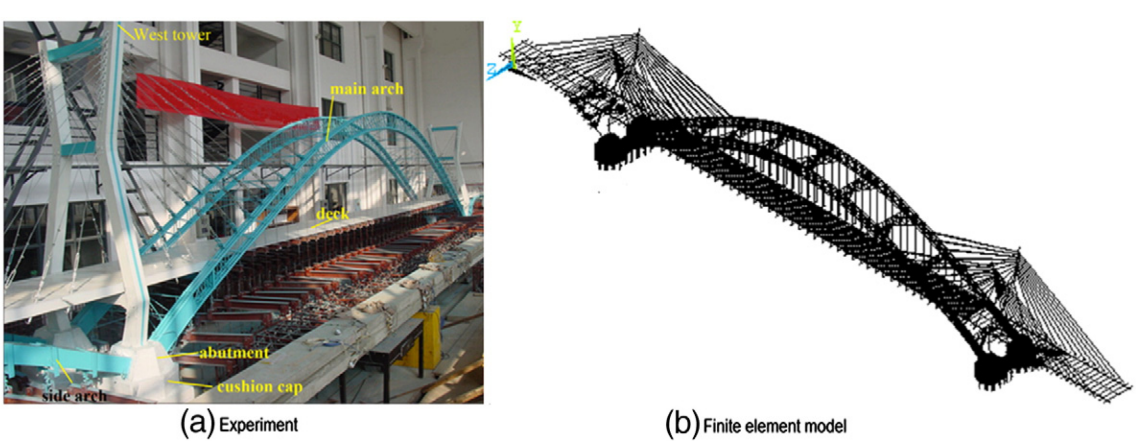

Fig. 1. Experimental and finite element model of the new type of cable-arch bridge.