Dynamic Testing and Modal Identification of a Concrete-filled Steel Tubular Arch Bridge under Natural Excitation

CHEN Yulin[a,1], CHEN Huiqin[a,2], HUANG Liwei[a,3]

[a] Department of Electronics, Chengxian College, Southeast University, Nanjing, 210088, China

[1]email: hyltz@sohu.com, [2]email: 41024257@qq.com, [3]email: liwei8203@163.com

Keywords: Arch bridge; Concrete-filled steel tubular; Natural excitation; Dynamic testing; Operational modal identification

Abstract. Rapid progresses have been made in design and erection technologies of concrete-filled steel tubular arch bridge in recent years. However, the research on dynamic properties of this type of bridge is far from mature. Generally, the dynamic properties are analyzed using numerical models. This paper presents the results of experimental study on dynamic properties of a concrete-filled steel tubular arch bridge. The dynamic testing of the bridge is performed by collecting acceleration responses stimulated by natural excitation. The sensor placement, the signal acquisition and measurement setups are given in detail. Dynamic properties, including modal frequencies and mode shapes of low-order modes, are identified from the ambient responses using frequency domain decomposition method. The identified modal properties could be used as initial state parameters in model updating, structural health monitoring or safety evaluation.

Introduction

Arch bridge is a historical type of bridge. The most famous arch bridge is Zhaozhou Bridge in China. The bridge was built in Sui Dynasty, fourteen hundreds of years ago. Zhaozhou Bridge and most of the ancient Chinese arch bridges are made of stones. This not only limits the spanning ability but also makes the building process complicated. With the application of steel and concrete, new types of arch bridge have been developed, including steel arch bridge, reinforcement concrete arch bridge and concrete-filled steel tubular (CFST) arch bridge. Among them, CFST arch bridge is the most promising type. Concrete-filled steel tube is designed to be the arch. The in-filled concrete delays the local buckling of the steel tube and the steel tube reinforces the concrete's resistance to tension, bending moment and shear force [1, 2]. This dramatically improved the loading capacity and spanning ability of arch bridge.

In 1990, the first CFST arch bridge of China, Wangcang Eastern River Bridge, was open to traffic in Sichuan Province. The main span of the bridge is 110m. Since then, the span of this type of bridge has increased rapidly [3]. In 2005, Wushan Yangste River Bridge was open to traffic in Sichuan Province. The main span of the bridge is 460m. The span refreshed the world record. In addition, there are more than twenty CFST arch bridges in China of which the spans exceed 300m. It is obvious that CFST arch bridge will definitely play an important role in the highway system of China. Therefore, it's necessary for civil engineering community to study further the static and dynamic properties of this type of bridge.

Research into CFST arch bridge has focused on the static behavior, thermal stress and erection techniques. However, there has been very little research into vibrations and seismic responses of CFST arch bridge [4]. Hence, the research on dynamic properties of this type of bridge is far from mature. Dynamic properties of CFST arch bridge are essentially important for the analysis of seismic and wind responses. Also, dynamic properties could be valuable information for structural health monitoring [5]. Generally, the dynamic properties are analyzed using numerical models [4], such as finite element model. Dynamic properties including modal frequencies and mode shapes are calculated using finite element analysis. And, seismic characteristics could also analyzed by using finite element models [4, 6]. In fact, the finite element analysis will in all possibility give results with errors because there are uncertainties in the material and structure, and there are assumptions in the modeling. To circumvent this problem, finite element model updating could be performed [7-9]. Even though, to fully investigate the dynamics properties, experimental study must be performed. But, in the past decades, very few results were published on experimental study of dynamic properties of CFST arch bridges [10].

This paper presents the experimental study on a CFST arch bridges in China. The dynamic testing of the bridge is performed. Structural responses excited by traffic and pedestrian loads are measured by accelerometers. Dynamic properties are identified using output-only modal identification method.

The CDL CFST Arch Bridge

The CFST arch bridge under consideration is located in Jiangsu Province, China. It’s a through tied-arch bridge. The bridge is nominated as CDL Bridge. In 2007, a project on bridge health monitoring and safety evaluation was initiated by the local Bureau of Public Works.

CDL Bridge was built in 1998. Figure 1 gives the photograph of the bridge. The bridge is actually consists of six spans. The main span is CFST arch bridge. The other five spans are simply supported beam bridges. The main span of the bridge is 50m. Two main arch ribs have the dimension of 920mm. The thickness of the steel tube is 18mm. Nine suspenders of steel wire ropes are vertically attached to main arch rib and tie beam on each of the river side. Each of these ropes consists of hundreds of bars. The concrete slabs are supported by eleven cross-girders. The length of cross-girder between two suspenders is nearly 15m. Two pre-stressed reinforcement concrete beam in the longitudinal direction act as tie beams. The cross-section of tie beams is mostly 1000x1900mm, but expanded to 1000x2500mm near the two ends of the beam. The tie beams are covered by steel plates with the thickness of 20mm.

Figure 1 CDL Bridge

To strengthen the stiffness in the transverse direction, four steel tubes are designed as wind braces to connect the two main ribs. The diameter of the tube is 250mm. And the thickness of the tube is 12mm. Each of the steel tube is mostly hollow but filled with concrete at the two ends connected with the ribs. The tubes are located at the middle position of the two near suspenders. Figure 2 gives the photograph of the four tubes. Only three of the tubes are visible due to the angle of the photograph.

Figure 2 Transverse Wind Brace of CDL Bridge

Dynamic Testing

As mentioned above, a health monitoring and safety evaluation project was initiated in 2007. During the process of the project, several tests are performed to investigate both the static and dynamic properties of the bridges. For static analysis, the strains of different locations under heavy trucks loads are measured using strain sensors. For dynamic analysis, the ambient acceleration responses under environmental excitations are measured using accelerometers.

The ambient vibration testing employs environmental excitation such as traffic, wind and pedestrians. This really decreased the cost of the test because no expensive excitation equipment is needed. And, the service of the bridge need not have to be interrupted. Hence, the ambient vibration testing is also nominated as operational vibration testing.

The equipments used in the tests include sensors, data acquisition system and signal processing system. The sensors are actually accelerometers (941B-type) manufactured by the IEM (Institute of Engineering Mechanics) of the China Earthquake Administration. The data acquisition and signal processing system are developed by the Anzheng Software Co. Ltd. Figure 3 gives the photograph of the data acquisition and signal processing system.

Figure 3 Data Acquisition and Signal Processing System

Measurement points are located at the upriver side and close to the joints of the suspenders and decks. As a result, there are 11 points for CDL Bridge. The accelerometers are installed on the surface of the bridge decks in the vertical direction. Figure 4 gives the sensor locations for CDL Bridge.

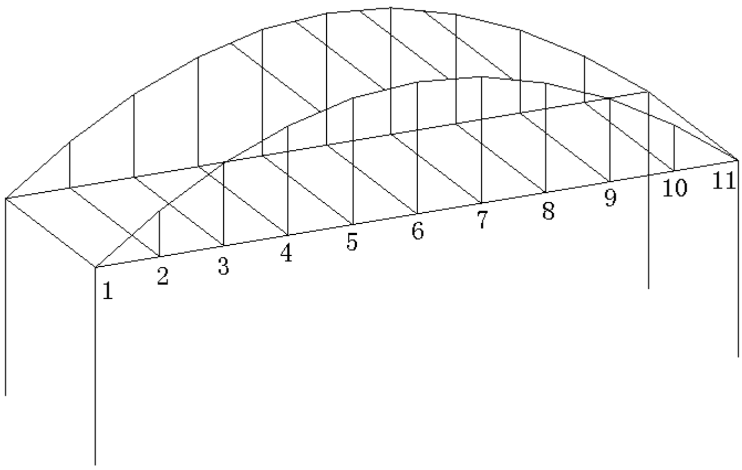

Figure 4 Sensor Locations for the CDL Bridge

Among all of the points, one is selected as reference point. Due to the limited channels of the acquisition system, two accelerometers are employed in the testing. One is fixed at the reference point; the other moveably measures the responses of other measurement points. That's to say, there're 10 setups for the test of CDL Bridge. Point 3# is the reference point.

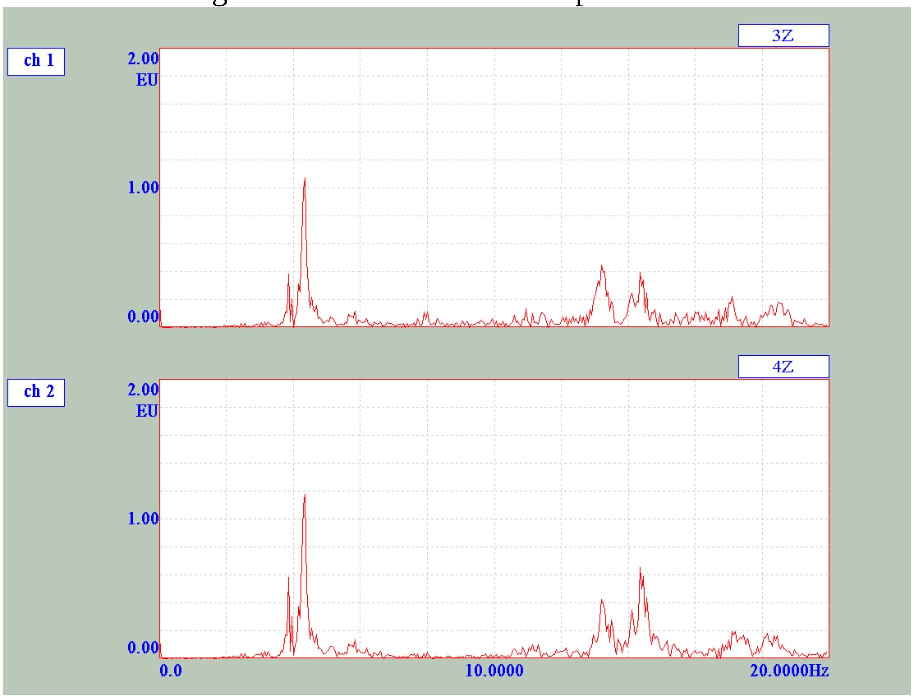

Figure 5 Auto-spectrum of the responses from Point 3# and Point 4#

Figure 5 is the auto-spectrum of the responses from Point 3# and Point 4#. It's obvious that there are only two modes within 10Hz.

Modal Identification of Two CFST Bridges

To extract modal parameters from ambient acceleration responses, output-only modal identification methods must be adopted because no input signals are measured. There're several kind of methods available including frequency domain methods, time domain methods and time-frequency domain methods [11-14]. In this study, the Frequency Domain Decomposition (FDD) [11] method is employed, which is a way to identify the modal parameters of a structure from responses only when the structure is loaded by a broad-banded excitation. Table 1 lists the identified modal frequencies and mode shape descriptions of the first two modes. Figure 6 and Figure 7 give the mode shapes.

Table 1 Identified Modal Frequencies and Mode Shapes

Mode Order	Frequency (Hz)	Mode Shape
1	3.8	Symmetric Bending
2	4.3	Asymmetric Bending

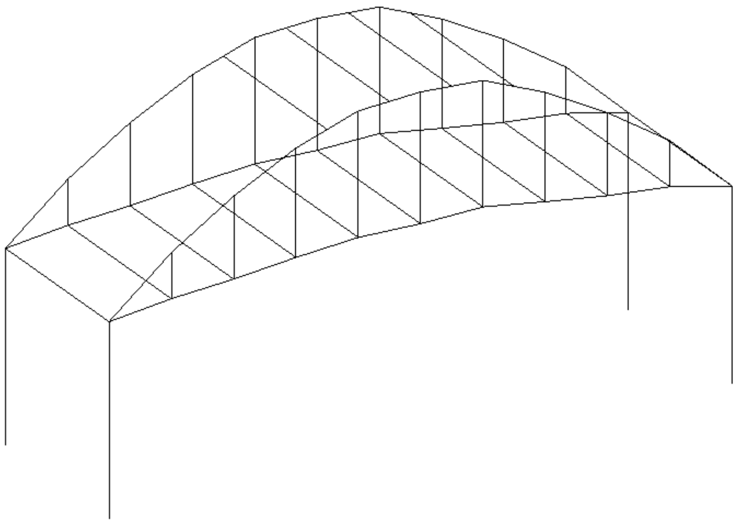

Figure 6 First Mode of CDL Bridge: Symmetric Bending

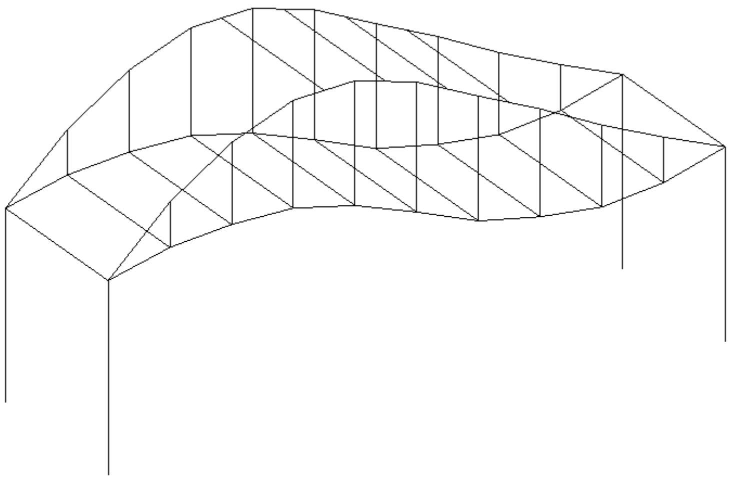

Figure 7 Second Mode of CDL Bridge: Asymmetric Bending

For a CFST arch bridge, the mode sequence is deterministic after its construction. But, during its service, the structural degradation will inevitably occur due to varieties of reasons, e.g., the overloaded trucks, the fatigue, the rust. The accumulated degradation could possibly lead to the changing of modal parameters. For example, the changing of vertical modes is closely related with damage in the arch ribs. Hence, the identified modal frequencies could be used as initial state parameters in structural health monitoring or safety evaluation. The frequency variation could be taken as an indicator for identification of damages in the arch rib.

Conclusion

Experimental study on dynamic properties of a concrete-filled steel tubular arch bridge is presented in this paper. Acceleration responses excited by environmental loads are recorded. Frequency Domain Decomposition method is employed to identify modal frequencies and mode shapes from the ambient responses. Since the changing of vertical mode is related with structural condition, the identified modal parameters could be used as initial state parameters in structural health monitoring and safety evaluation.

Acknowledgements

This work was financially supported by the General Project of Natural Science Foundation of Colleges and Universities in Jiangsu Province (16KJB510002) and Young teachers' Research and Development Foundation of Southeast University Chengxian College (y310001).

References:

[1]. C. W. Roeder, B. Cameron and C. B. Brown, Composite action in concrete filled tubes, Journal of Structural Engineering, 125(5):477-484, 1999.
[2]. A. H. Varma, J. M. Ricles, R. Sause and L. W. Lu, Experimental behavior of high strength square concrete-filled steel tube beam-columns, Journal of Structural Engineering, 128(3):309-318, 2002.
[3]. Z. Zhen, B. Chen and Q. Wu, Recent development of CFST arch bridge in China, Proceedings of the 6th ASCCS Conference, USA, 205-212, 2000.
[4]. Mistuhiro Yoshimura, Qingxiong Wu, Kazuo Takahashi, Shozo Nakamura and Kazuyoshi Furukawa, Vibration analysis of the second Saikai Bridge- a concrete filled tubular (CFT) arch bridge, Journal of Sound and Vibration, 290:388-409, 2006.
[5]. S. W. Doebling, C. R. Farrar, M. B. Prime, D. W. Shevitz, Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review, Research Report, LA-13070-MS, Los Alamos National Laboratory, Los Alamos, N.M., 1996.
[6]. Qingxiong Wu, Mistuhiro Yoshimura, Kazuo Takahashi, Shozo Nakamura and Tadashi Nakamura, Nolinear seismic properties of the second Saikai Bridge: A concrete filled tubular arch bridge, Engineering Structures, 28:163-182, 2006.
[7]. Zhou-Hong Zong, Bijaya Jaishi, Ji-Ping Ge and Wei-Xin Ren, Dynamic analysis of a half-through concrete-filled steel tubular arch bridge, Engineering Structures, 27:3-15, 2005.
[8]. Bijaya Jaishi, Hyo-Jin Kim, Moon Kyum Kim, Wei-Xin Ren, Sang-Ho Lee, Finite element model updating of concrete-filled steel tubular arch bridge under operational condition using modal flexibility, Mechanical System and Signal Processing, 21:2406-2426, 2007.
[9]. Bijaya Jaishi and Wei-Xin Ren, Structural finite element model updating using ambient vibration test results, Journal of Structural Engineering, 131:617-628, 2005.
[10]. Jiangling Fan, Zhiyi Zhang and Hongxing Hua, Data processing in subspace identification and modal parameter identification of an arch bridge, Mechanical System and Signal Processing, 21:1647-1689, 2007.
[11]. P. Van Overschee, B. De Moor, Subspace identification for linear system: Theory-Implementation-Applications, Kluwer Academic Publishers, Dordrecht, Netherlands, 1996.
[12]. R. Brincker, Ling-Mi Zhang, Modal Identification of output-only systems using frequency domain decomposition, Smart Materials and Structures, 10:441-445, 2001.
[13]. J. Lardies, S. Gouttebroze, Identification of modal parameters using the wavelet transform, International Journal of Mechanical Sciences, 44:2263-2283, 2002.
[14]. Q. G. Fei, Output-only modal identification and its application in structural health monitoring of Runyang Cable-supported bridge, Postdoctoral Research Report, Southeast University, 2007.