Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Modal identification of a twelve span viaduct in two different construction stages via ambient dynamic testing

Xinghua Chen[1], Piotr Omenzetter[2], and Sherif Beskhyroun[1]

[1] The University of Auckland, Auckland, New Zealand
[2] The LRF Centre for Safety and Reliability Engineering, University of Aberdeen, Aberdeen, UK

ABSTRACT: This paper presents the results of modal identification tests that were performed in a twelve span viaduct, located in Auckland, New Zealand, during construction and after completion. These tests are two extensive one-off ambient vibration tests using wireless sensors, conducted to evaluate the structural behavior of the viaduct. The modal identification tests comprised the measurement of accelerations in the structure induced by the usual vehicular traffic crossing over the viaduct. Output-only modal identification methodologies were used to analyze the data obtained in those tests, in order to identify the modal properties of the viaduct in the two different stages.

1 INTRODUCTION

During the last decades, due to the ageing of a large number of structures and the increasing complexity of new bridges, considerable research efforts have been devoted to observing the in-situ dynamic behavior of bridges. Experimental measurement tests are used to determine the structural properties at the time of opening and during the life time of bridges under dynamic loads, such as wind, earthquake or traffic. It allows researchers to compare the dynamic characteristics assumed in the design with those of experimental test (Clemente et al. 2002).

There are two general types of methods that have been used in bridge dynamic tests, namely, the forced vibration tests and the ambient vibration tests (Farrar et al. 1999). Despite relatively small amplitudes of response, ambient vibration tests usually provide reliable and accurate estimates of natural frequencies and mode shapes of large bridges at certain stages of their lifetime, normally construction, commissioning or rehabilitation (Cunha et al. 2007). The estimated dynamic parameters are used for establishing correlations with numerical predictions or in some cases developing and updating of finite element models (Gentile 2006, Altunisik et al. 2011, Liu et al. 2011, Magalhães et al. 2012). Such tests can help to characterize the baseline condition of the structural behavior, allowing subsequent detection of structural changes.

Among the flexible structures, long-span, concrete bridges are one common type. For the design of such type of structures, the dynamic and vibrational load effects are especially important factors, which must be carefully considered in the design. The ability to accurately predict the dynamic response of the structure to various critical transient load effects, such as wind and earthquake and traffic induced vibrations, is essential for a safe and high performance design. The recent construction of the Newmarket Viaduct in Auckland, New Zealand, a major 12-span, 690m long, post-tensioned highway bridge, created an excellent opportunity to evaluate in-situ performance of such structures.

As a part of a comprehensive monitoring and research project on the behavior and performance of the Newmarket Viaduct (Chen and Omenzetter 2013), this paper describes a preliminary study of data from two ambient dynamic tests. This included the development of two extensive one-off ambient vibration tests using wireless sensors that provided important information for the construction of a numerical model of the bridge that was “tuned” to fit the bridge dynamic properties identified by the ambient vibration tests. This numerical approach was essential to improve the understanding of the structure dynamic behavior and to create a baseline model for future condition assessment studies.

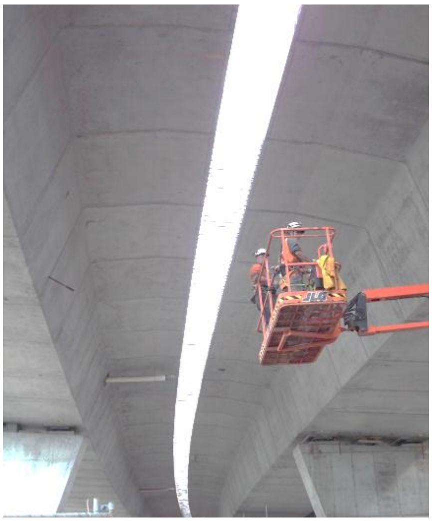
In this paper the Newmarket Viaduct is briefly described. Next, the dynamic testing procedures are presented. The following sections address the modal identification techniques that were applied, and the comparison of the dynamic characteristics evaluated in 2011 and in 2012, i.e. before and after the in-situ concrete ‘stich’ that now joins the two parallel bridges making up the viaduct was cast. Finally, some conclusions and future research directions are presented.

2 DESCRIPTION OF THE VIADUCT

The Newmarket Viaduct, recently constructed in Auckland, New Zealand, is one of the major and most important bridges within the country’s road network. It is a horizontally and vertically curved, post-tensioned concrete bridge, comprising two parallel, twin bridges. The Southbound Bridge was constructed first and opened to traffic at the end of 2010; this was followed by the construction of the Northbound Bridge completed in January 2012. Now, both bridges are opened to traffic. The traffic on the Northbound deck is carried on three lanes, and on four lanes on the Southbound deck. A view of the Newmarket Viaduct appears in Figure 1.

Figure 1. Newmarket Viaduct

The total length of the bridge is 690m, with twelve different spans ranging in length from 38.67m to 62.65m and average length of approximately 60m. Construction of the bridge consumed approximately 4,200t of reinforced steel, 544km length of stressing strands, and 30,000m^3 of concrete. The superstructure of the bridge is a continuous single-cell box girder of a total width of 30m. The deck of the bridge contains a total of 468 precast box-girder segments and was constructed with balanced cantilever and prestressed box-beam method. The Northbound and Southbound Bridges are supported on independent pylons and joined together via a cast in-situ concrete ‘stitch’. Figure 2 shows images of the bridge soffit before and after casting of the ‘stitch’.



(a) before

(b) after

Figure 2. Soffit of Northbound and Southbound Bridges: a) before, and b) after casting of in-situ concrete 'stitch'

3 AMBIENT VIBRATION TESTS

A comprehensive ambient vibration testing program was conducted in two phases. The first one was carried out in November 2011 (Test 1), just before casting the in-situ concrete 'stitch' between the two bridges, and only included testing of the Southbound Bridge. The second one was carried out in November 2012 (Test 2), conducted just before project completion and after casting of the 'stitch', covering both bridges (the Southbound Bridge and the Northbound Bridge). However, for comparison only the results from the Southbound Bridge are discussed in this paper.

The two extensive one-off ambient vibration test campaigns were carried out in Newmarket viaduct to determine the actual bridge dynamic characteristics at a construction stage and for the final state. A similar testing procedure was adopted in the two tests, although with some slight differences. The accelerometers used for both tests were 56 USB wireless accelerometers developed by the Gulf Coast Design Concepts (http://www.gcdataconcepts.com/products.html). Those sensors have a reasonably large internal data storage capacity but do not transmit data wirelessly. Data need to be transferred to a computer after completion of a test via an USB connection. All the measurements points in both tests chosen for placing accelerometers were on each side of the bridge girder. Figure 3 shows accelerometers inside the bridge girder during Test 2.

The tests were carried out with four reference locations in span 6 and span 7 during all the test set-ups that were performed, while the remaining accelerometers were moved to different points. In total, acceleration measurements were taken at 96 points in the 2011 tests and 72 points in the 2012 tests. Five test setups were used to cover the planned testing locations of the Southbound Bridge in Test 1, but only three setups in Test 2. In both tests the sampling frequency was 160Hz and corresponding recording times were all approximately 1 hour for each setup.

Figure 3. Accelerometers inside bridge girder in Test 2

4 MODAL IDENTIFICATION OF THE VIADUCT

4.1 Data pre-processing

Before applying an output-only modal identification method, the acceleration records were preprocessed with the following operations: 1) Mean removal, detrending and high pass filtering to remove noise below 1Hz; 2) Low pass filtering at 20Hz with a 5 pole Butterworth filter; and 3) Decimation from the 160Hz sampling rate used in the tests to 50Hz.

4.2 Output only modal identification

Although in Test 1 the modal identification analysis of the tests data was performed using Stochastic Subspace Identification (SSI) and Peak Picking (PP) (Chen etc. 2012), this time it was decided to apply the enhanced frequency domain decomposition method (EFDD) (Jacobsen et al. 2007) available in an in-house system identification toolbox written in MATLAB (Beskhyroun 2011). It was also decided to do a reanalysis of the Test 1 data using also the EFDD method so that the comparison of the identified dynamic characteristics, before and after the in-situ casting of concrete 'stitch' between two bridges, could be more meaningful. The modal identification analysis was performed considering separately the vertical and the transverse records.

The EFDD method procedures were applied to the peaks identified in the singular value spectra in order to evaluate the frequencies and shapes of the natural modes of vibration of the viaduct. For Test 1 data, it was possible to identify 13 modes of vibration, while for Test 2 data, only 12 modes. The frequencies and general characteristics of the identified modes of vibration are presented in Table 1 for the tests performed before and after casting of the in-situ concrete 'stitch' between the two bridges. (Note the modes have been listed in the increasing frequency order for each test separately, but this resulted in modes of similar shapes from Test 1 and 2 not necessarily having the same number.) Figures 4 to 7 show a comparison of mode shapes identified before and after the in-situ casting of concrete 'stitch' for the first two vertical and the first two transverse modes. In those figures, side L means the side of the Southbound Bridge adjacent to the 'stitch', and side R means the side of the Southbound Bridge facing outwards. Considering the dynamic characteristics identified with the EFDD method applied to the data of the tests performed before and after the in-situ casting of concrete 'stitch' between two bridges, the following observations can be made. The frequencies of the first two transverse modes have increased markedly from 1.64Hz to 2.14Hz and from 2.11Hz to 3.44Hz, respectively. The frequencies of the first two vertical modes have decreased slightly, from 2.15Hz to 2.03Hz and from 2.42Hz to 2.34Hz, respectively. In the transverse direction, after casting of the in-situ concrete 'stitch', the two bridges work as one whole structure, which increase the stiffness of the structure more than the corresponding increase in inertia. As a result, the transverse frequencies increase. For vertical modes, the increase in stiffness and inertia are similar and so the changes in the vertical frequencies are not significant.

It also can be seen that the identified mode shapes agree well between the two tests. However, there is still a difference in the transverse deformability of the viaduct, which can be seen in the mode shapes identified for the second transverse vibration mode. The modal components identified for that mode are different at the ends of the four spans. For Test 2, the amplitude at the end of the four spans is much larger than for Test 1.

Table 1. Dynamic characteristics identified in Test 1 and Test 2

Test 1			Test 2		
Mode	Type of Mode	f/Hz	Mode	Type of Mode	f/Hz
Mode 1	Transverse	1.64	Mode 1	Vertical	2.03
Mode 2	Transverse	2.11	Mode 2	Transverse	2.14
Mode 3	Vertical	2.15	Mode 3	Vertical	2.34
Mode 4	Vertical	2.42	Mode 4	Vertical	2.54
Mode 5	Vertical	2.62	Mode 5	Vertical	2.81
Mode 6	Transverse	2.73	Mode 6	Vertical	3.12
Mode 7	Vertical	2.89	Mode 7	Vertical	3.32
Mode 8	Vertical	3.20	Mode 8	Transverse	3.44
Mode 9	Vertical	3.52	Mode 9	Vertical	3.67
Mode 10	Transverse	3.63	Mode 10	Vertical	3.83
Mode 11	Vertical	3.75	Mode 11	Vertical	4.30
Mode 12	Vertical	4.20	Mode 12	Vertical	7.46
Mode 13	Vertical	6.88			

5 CONCLUSIONS AND FUTURE RESEARCH

This paper presents the dynamic tests performed on a 12-span viaduct in two different stages (before and after the two bridges making up the viaduct are joined together via a cast in-situ concrete 'stitch'). The dynamic characteristics identified in both cases were presented and compared in order to determine the actual bridge dynamic characteristics during construction and for the final state. The frequencies of the first two transverse modes have increased markedly, whereas the frequencies of the first two vertical modes decreased, but only slightly. These two preliminary ambient vibration tests are essential for calibration of a numerical model of the viaduct. They indicated the effect of structural modifications occurring during the structure's construction process and provided important baseline data for stakeholders to apply vibration based condition assessment techniques. The numerical model to be developed and calibrated using the presented test results will also be a fundamental tool in those future analyses.

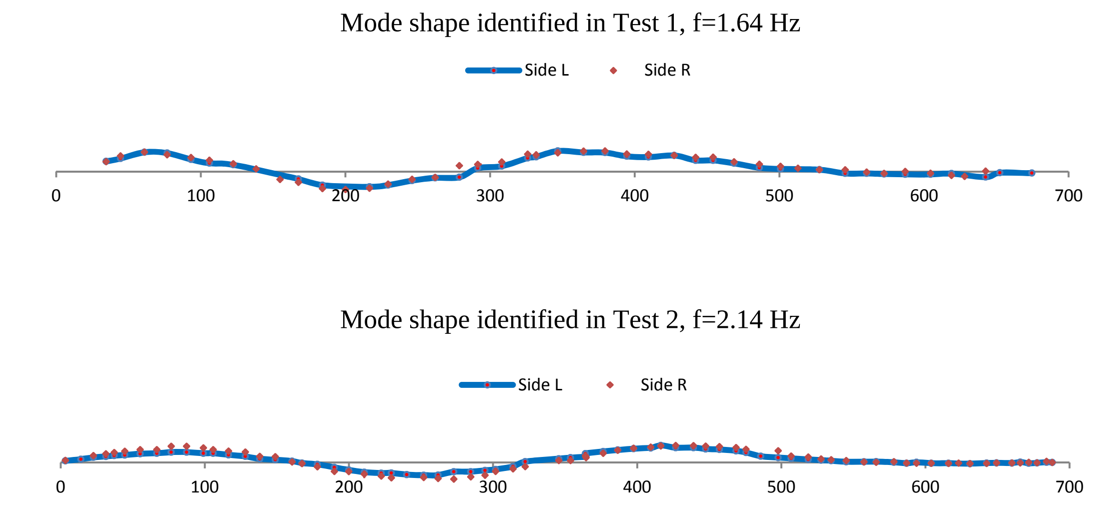


Figure 4. Mode shapes for the first transverse mode

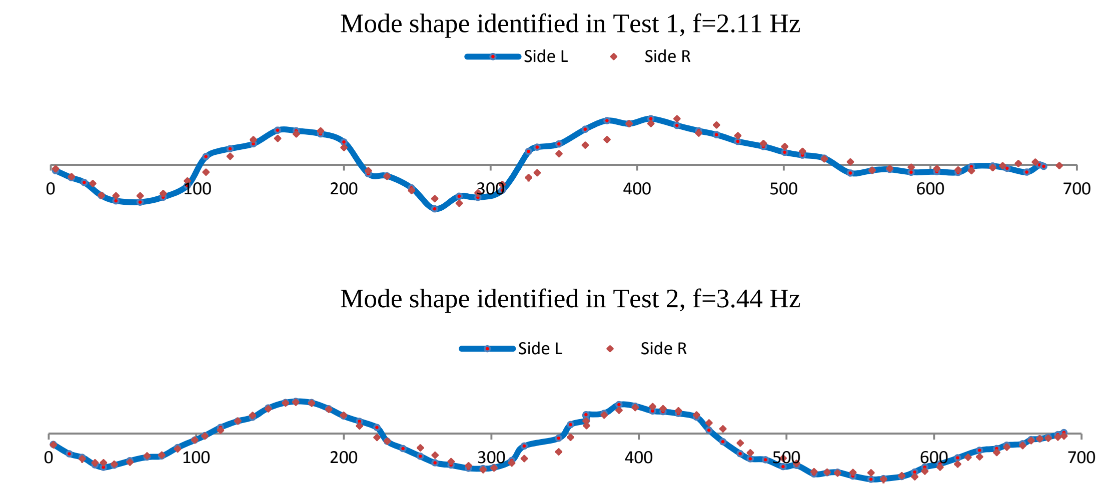


Figure 5. Mode shapes for the second transverse mode

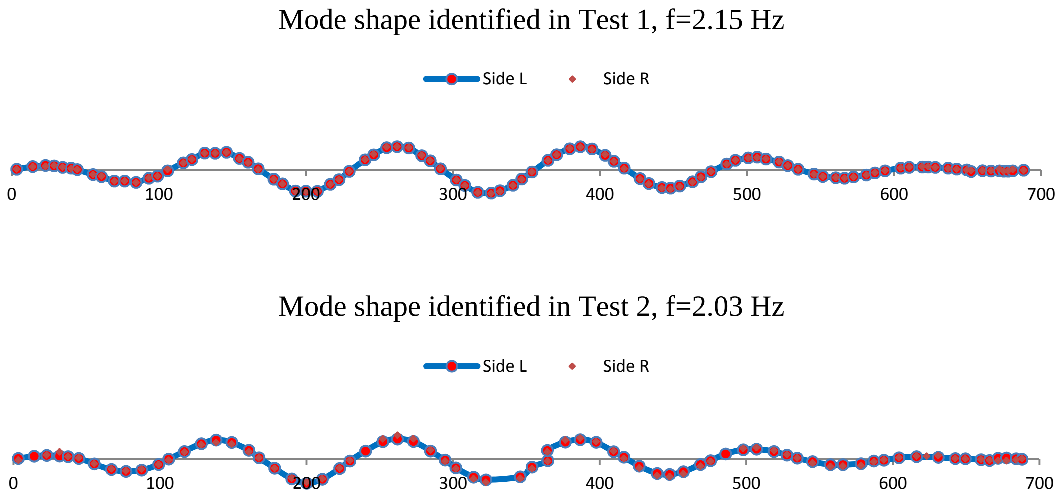


Figure 6. Mode shapes for the first vertical mode

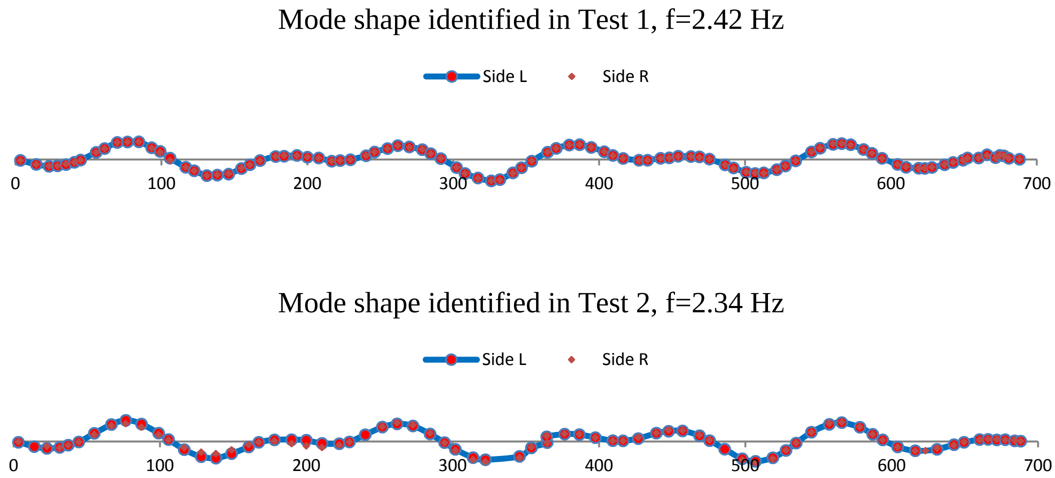


Figure 7. Mode shapes for the second vertical mode

6 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to their supporters. Research work at the University of Auckland was supported by the Earthquake Commission Research Foundation grant UNI/578. Piotr Omenzetter's work within The LRF Centre for Safety & Reliability Engineering at the University of Aberdeen is supported by The Lloyd's Register Foundation (The LRF). The LRF supports the advancement of engineering-related education, and funds research and development that enhances safety of life at sea, on land and in the air. NGA Newmarket facilitated the field testing and New Zealand Transport Agency allowed the use of

Newmarket Viaduct for research. Gewei Chen, Shahab Ramhormozian and Peifen Chua, research students at the University of Auckland, assisted with the ambient vibration tests.

7 REFERENCES

Altunisik, A., Bayraktar, A., and Sevim, B. 2011. Output-only system identification of post tensioned segmental concrete highway bridge. Journal of Bridge Engineering, 16(2): 259-266.

Beskhyroun, S. 2011. Graphical interface toolbox for modal analysis. In: Proc. of the 9th Pacific Conference on Earthquake Engineering: Building an Earthquake-Resilient Society. Auckland, New Zealand, paper no. 077.

Chen, X., and Omenzetter, P. 2013. A framework for reliability assessment of an in-service bridge using structural health monitoring data. Key Engineering Materials, 558: 39–51.

Chen, X., Omenzetter, P. and Beskhyroun, S. 2012. Ambient vibration tests and analysis of a multiple-span elevated bridge. In: Proc. of the 22nd Australasian Conference on the Mechanics of Structures and Materials. Sydney, Australia. 393-398.

Clemente, P., Marulo, F., Lecce, L., and Bifulco, A. 1998. Experimental modal analysis of the Garigliano cable-stayed bridge. Soil Dynamics and Earthquake Engineering, 17(7-8): 485–493.

Cunha, A., Caetano, E., and Magalhães, F. 2007. Output-only dynamic testing of bridges and special structures. Structural Concrete, 8(2): 67–85.

Farrar, C., Duffey, T., Cornwell, P. and Doebling, S. 1999. Excitation methods for bridge structures. In: Proc. of the 17th International Modal Analysis Conference, Kissimmee, USA, 1063-1068.

Gentile, C. 2006. Modal and structural identification of a RC arch bridge, Structural Engineering and Mechanics, 22(1): 53-70.

Jacobsen N., Andersen P. and Brincker R. 2007. Using EFDD as a robust technique to deterministic excitation in operational modal analysis. In: Proc. of the 2nd International Operational Modal Analysis Conference (IOMAC) Copenhagen, Denmark, 193-200.

Liu, T., Chiang, W., Chen, C., Hsu, W., Lu, L., and Chu, T. 2011. Identification and monitoring of bridge health from ambient vibration data. Journal of Vibration and Control, 17(4): 589-603.

Magalhães, F., Caetano, E., M., Cunha, A., Flamand, O. and Grillaud, G. 2012. Ambient and free vibration tests of the Millau Viaduct: Evaluation of alternative processing strategies. Engineering Structures, 45: 372-384.