Experimental and analytical modal analysis of a multiple-span motorway bridge

G W. Chen  
University of Auckland

S Beskhyroun  
University of Auckland

P Omenzetter  
University of Aberdeen

Publication details
EXPERIMENTAL AND ANALYTICAL MODAL ANALYSIS OF A MULTIPLE-SPAN MOTORWAY BRIDGE

G.W. Chen*
Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. gche870@aucklanduni.ac.nz (Corresponding Author)

S. Beskhyroun
Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. s.beskhyroun@auckland.ac.nz

P. Omenzetter
The LRF Centre of Safety and Reliability Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK. piotr.omenzetter@abdn.ac.uk

ABSTRACT

The paper presents the experimental and analytical modal analysis for an eleven-span continuous concrete deck bridge in New Zealand. Sine-sweep forced-vibration testing by rotating weight shakers was conducted to excite the bridge within the frequency band of interest. One of the most advanced time domain system identification techniques, i.e. the data-driven stochastic subspace identification, was used to extract the modal parameters of the bridge. Correlation analysis among the developed beam-element girder, shell-element girder models and experimental measurements was carried out in terms of natural frequencies and mode shapes, and a good agreement was achieved. This suggests that both developed numerical models have adequate accuracy from the point of view of engineering practise for precisely calculating dynamic response in different circumstances, such as earthquakes and traffic loading, as long as linear response range is considered.

KEYWORDS

Modal analysis, bridge, stochastic subspace identification, finite element model.

INTRODUCTION

The construction of curved-girder bridges offers a common solution for fitting large, complex, highway/motorway interchanges into densely populated areas throughout the country. Guaranteeing an adequate safety level for such new constructed and existing bridges is of paramount importance, since this type of bridge structures serve as the underpinnings of current highly industrialized society. Static characteristics of bridges, such as strength and stability, cannot fully reflect the actual structural performance under operational conditions, and failures of bridges associated with their dynamic behaviour were frequently reported, such as the collapse of the newly built Tacoma Narrows Bridge in 1940 due to wind excitations (Smith 1976). Consequently, it is important to develop an advanced understanding of dynamic behaviour of bridge structures under vibration loading effects, which can be achieved by modal analysis, a technique that estimates the dynamic characteristic (modal parameters) of a structure, i.e. natural frequencies, damping ratios and mode shapes (Ren et al. 2005). Modal analysis generally includes analytical and experimental investigations, which are the two complementary means to create enhanced understanding of the real dynamic behaviour of constructed structural systems. Normally, analytical modal analysis determines the dynamic properties of a
structure based on the eigenvalue analysis of the equations of motion, for which the finite element (FE) method has been accepted as a practical numerical analysis tool due to the tremendous improvements in computing power in the last several decades (Brownjohn et al. 2003; Butt and Omenzetter 2014). The calculated eigenvalue/eigenvector pairs based on the developed FE model can be used as the guidance or checking of design assumptions during the normal design procedure in civil engineering practice. In addition, the mechanisms responsible for the measured performance of the full-scale bridge can be identified by detailed computer modelling. On the other hand, experimental modal analysis identifies the dynamic properties of a structure from in situ dynamic measurements based on modal extraction techniques. The experimentally identified modal parameters from the prototype testing can add to the body of knowledge about the as-built performance of the structure, and provide abundant information whether the structure performs as predicted during design. By correlating the measured data with the numerical models, the created models can be evaluated. Notwithstanding the advantages of implementing the modal analysis for civil engineering infrastructures, some unique attributes of constructed structural systems, such as complexity, large size and low resonant frequencies, pose great challenges to practitioners. One of the uncertainties and challenges arises from the fact that unlike the large numbers of identical structural units in automobile, airplane and similar industries every bridge structure is actually a unique prototype. In other words, each built bridge has its own distinctive dynamic behaviours, and different problems pertaining to FE modelling, modal testing, modal parameter identification may emerge, which will require a rather wide range of skills and expertise in the relevant areas.

The objective of this paper is to present an application of experimental and analytical modal analysis for a multi-span, curved girder motorway bridge located in the CBD of Auckland, New Zealand. The structural characteristics of the bridge and the procedure of sine-sweep forced-vibration testing are firstly described. The dynamic characteristics of the bridge are then extracted from the time domain stochastic subspace identification (SSI) method. The analytical work involved the development and modal analysis of the two types of FE model (beam-element and shell-element model). Correlation analysis among the developed beam-element girder, shell-element girder models and experimental measurements was carried out in terms of natural frequencies and mode shapes, and a good agreement was found.

BRIDGE DESCRIPTION

The bridge under survey, the Nelson St off-ramp, links the Northern Motorway to Auckland’s port and North-Western Motorway. Figure 1a shows the aerial and side view of the bridge, which is a curved, post-tensioned, continuous concrete structure with a hollow box section girder. Fig 1b shows the pot type structural bearings installed on top of a pier to support the superstructure. An elevation sketch showing span lengths and pier heights is displayed in Figure 2. Two different precast cross-section of the segmental girder were used and connected via a hinge located between Pier 4 and 5. The hinge consists of fixed type pot bearings supported on a mild steel I section cantilever welded to the girder on the other side. The fixed type pot bearing, which provides rotational capacity only, was used at Piers 1, 2, 4, 6, 7, 8, 9, 10 and Abutment 2. The sliding type pot bearing, which provides rotational capacity and free sliding in one direction only, was used at Piers 3, 5 and Abutment 1. Pile foundation was constructed under Pier 1-3, and footing of Piers 4-10 was placed directly on prepared fill.

![Figure 1. Nelson St off-ramp bridge: a) aerial and side view, and b) pot bearing and shear key](image-url)
FIELD DYNAMIC TESTING AND MODAL IDENTIFICATION

Two ANCO MK-140-10-50 eccentric mass exciters (Ma et al. 2007) (in horizontal and vertical configuration respectively) were anchored on the bridge deck (Figure 3a) to excite the bridge structure in both the vertical and lateral direction in the frequency range of up to 10 Hz. Both of the shakers were positioned on the longest span between Pier 2 and 3 (see Fig. 2) selected based on a preliminary FE modal analysis to avoid nodal points of the expected mode shapes as much as possible. During the sweeping excitation process, the frequency increment was set as 0.1 Hz, and each frequency increment was held around 20 seconds with a 5 second ramp up time from the previous excitation frequency. This excitation protocol allowed the bridge to achieve steady state response at each excitation frequency increment. During vertical sweeping, 62 MEMS accelerometers (Haritos 2009; Beskhyroun and Ma 2012) were arranged along both curbs of the bridge deck (Fig. 3b). Representative position of each bridge span (eg.1/2 and 1/4 span-length points) were preferably chosen as the measuring locations. During lateral sweeping testing, all accelerometers were arrayed along the midline of the bridge deck with around 4 m spacing to achieve a better spatial resolution as well as to capture possible higher mode responses. One of the most advanced modal identification techniques, namely data-driven SSI was used to extract natural frequencies, damping ratios and mode shapes (Van Overschee and De Moor 1996). The SSI algorithm directly works with time domain data and extracts a system model in the state space. After the identification of the state space model, the modal parameters are obtained from the system matrices using eigenvalue analysis. To conveniently deal with the acceleration time data, a MATLAB based system identification toolbox was developed at the University of Auckland (Beskhyroun 2011).

FINITE ELEMENT MODELLING

In many cases, a number of physically reasonable and different models are capable of correlating the experimental data with their analytical predictions. As a result, in the present work two different types of FE models for the bridge, i.e. a beam-element girder model and a shell-element girder model are developed in ANSYS (2012). The geometry and structural properties of the models are estimated from the design drawings. The built numerical models are shown in Figure 4. For the beam-element girder model, the main structural components, such as box section bridge girders and hexagon section piers, are modelled by using 2 node 3D elastic beam elements (Beam188). Non-structural members, such as...
steel rails, asphalt layer and concrete water channel, are considered as concentrated masses evenly distributed along bridge longitudinal direction and modelled by 3D point elements (Mass21) without rotary inertia, while their stiffness contributions are not included for simplicity. The rotational capability of the hinge in the vertical and lateral bending planes and for torsion is modelled as three linear elastic spring elements (Combin14), considering the actual hinge is most likely not a perfect hinge that allows the connection joint to rotate completely freely. The fixed type and sliding type pot bearing of the bridge is modelled by coupling the corresponding translational degrees of freedom (DOF) at nodes of both pier and girder. Pier footings are modelled as fully fixed at the base considering solid rock foundation by constraining all DOF of the corresponding nodes. The soil-structure interaction, piles, abutments and pre-stressed forces in the concrete are not included in the analysis. The bridge girder is discretized with into 0.1m long elements, and piers are discretized into 0.2m long elements. Subsequently, 3,920 nodes, 3,460 elements (3,314 beam elements, 143 mass elements, and 3 spring elements) are used.

In the shell-element model, the box girder and the asphalt pavement are modelled by 3D four node shell elements (SHELL 63). Piers, steel rails, and concrete water channel are modelled by beam elements (BEAM188). At the hinge location, coupling of the translational displacement of corresponding nodes is introduced. The fixed type and sliding type pot bearing is modelled by coupling the corresponding translational DOF at nodes of both the pier and girder. Pier footings are modelled as fully fixed at the base by constraining all DOF of the corresponding nodes. As a result, the shell-element model consists of 58,665 nodes and 66,064 elements (57,280 shell elements, 8,784 beam elements).

Figure 4. Numerical models of the Nelson St off-ramp Bridge: a) beam-element model, and b) shell-element model

COMPARISON OF EXPERIMENTAL AND NUMERICAL MODAL PARAMETERS

A shifted Block-Lanczos method (Grimes et al. 1994) in ANSYS is chosen to extract the eigenvalue/eigenvector pairs from the FE models. The correlation between modal parameters identified from the test and those calculated numerically is evaluated by comparing the values of the natural frequencies and similarity of mode shapes. In terms of the comparative analysis of mode shapes, the Modal Assurance Criterion (MAC) is used (Allemang and Brown 1982). Table 1 summarizes these comparisons, where the labels V, L and T stand for vertical bending, lateral bending and torsional mode, respectively. It can be observed all the modes identified experimentally have their counterparts in both types of FE models. The error column shows that the general trend for natural frequency and mode shape differences between experimental and numerical results is relatively small for the lower modes but increases the higher modes. The MAC values are higher for the lower modes than for the higher modes too. This demonstrates that much bigger difficulty exists for reliably obtaining higher modes from either the measurements or the FE models. The reasons can include: higher modes may involve more complex vibration mechanisms or non-structural member contributions; and the measurement accuracy of higher modes is relatively low and more vulnerable to testing noise. The vertical modes have relatively lower frequency errors compared to the lateral modes, which indicates that the created FE models capture better the mass and stiffness distribution for the vertical direction. For both the beam- and shell-element models, the analytical natural frequencies of
the vertical modes are slightly lower than their corresponding values from the test. This may be because only the mass effect of non-structural components is taken into account while neglecting their stiffness contributions, or the assumed material parameter values deviate from their actual values. For the shell-element girder model, the MAC values are generally slightly higher than that of the beam-element model for the lateral modes, which indicates that shell-element girder model may be more efficient in reproducing the dynamic behaviour of these modes. In addition, the shell-element model better captures the shape of the torsional mode $T_1$ as well as the local distortional behaviours of the bridge that the beam model is unable to duplicate. The MAC of the first four vertical modes ($V_1$, $V_2$, $V_3$ and $V_4$) and the first three lateral modes ($L_1$, $L_2$ and $L_3$) for both types of FE models are above 0.85, which shows a good correlation between the numerical and the experimental results, since MAC values as low as 0.70 are often accepted in civil engineering applications due to imperfect measurements typically made in noisy environments and challenges of accurate FE modelling (Zivanovic et al. 2005). Because dynamic responses of bridge structures are generally dominated by the lowest few modes in external excitation events, the good agreement between experimental results of the lowest few modes and their numerical counterparts shows that the both developed numerical models have adequate accuracy in engineering practise for precisely calculating dynamic response in different severe circumstances, such as earthquakes and traffic loading.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal testing</th>
<th>FE analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modal testing</td>
<td>FE analysis</td>
</tr>
<tr>
<td></td>
<td>Frequency/Hz</td>
<td>Frequency/Hz</td>
</tr>
<tr>
<td>V1</td>
<td>3.18</td>
<td>3.09</td>
</tr>
<tr>
<td>V2</td>
<td>3.91</td>
<td>3.84</td>
</tr>
<tr>
<td>V3</td>
<td>4.19</td>
<td>4.11</td>
</tr>
<tr>
<td>V4</td>
<td>4.79</td>
<td>4.72</td>
</tr>
<tr>
<td>V5</td>
<td>5.66</td>
<td>5.44</td>
</tr>
<tr>
<td>V6</td>
<td>7.15</td>
<td>7.03</td>
</tr>
<tr>
<td>V7/T1</td>
<td>7.92</td>
<td>8.44</td>
</tr>
<tr>
<td>L1</td>
<td>1.86</td>
<td>2.12</td>
</tr>
<tr>
<td>L2</td>
<td>2.56</td>
<td>2.78</td>
</tr>
<tr>
<td>L3</td>
<td>3.65</td>
<td>3.62</td>
</tr>
<tr>
<td>L4</td>
<td>4.54</td>
<td>4.60</td>
</tr>
<tr>
<td>L5</td>
<td>5.57</td>
<td>5.81</td>
</tr>
<tr>
<td>L6</td>
<td>6.61</td>
<td>7.38</td>
</tr>
<tr>
<td>L7</td>
<td>7.61</td>
<td>8.28</td>
</tr>
<tr>
<td>L8</td>
<td>9.32</td>
<td>11.70</td>
</tr>
</tbody>
</table>

CONCLUDING REMARKS

The following conclusions are drawn from the modal analysis performed on the full scaled multiple-span motorway bridge:

- The analytical and experimental modal analysis provided a comprehensive investigation of the dynamic properties of bridge. The analytical model analysis through three dimensional FE modelling gives a detailed description of the physical and modal characteristics of the bridge, while experimental modal analysis through the in-situ experimentation creates knowledge about the actual performance of the structural system, which is used for evaluating the drawing-based idealized FE model.

- The forced vibration tests by using large eccentric mass shaker are able to efficiently excite the vibration modes in the frequency range of interest of the multiple- span reinforced concrete bridge structure, when the placement of shakers is carefully selected based on preliminary FE modal analysis to avoid nodal point of expected mode shapes.

- Both of the developed FE models, i.e. beam-element model and shell-element model, replicate well experimental data, while the shell-element model captures better the torsional mode.
• The divergence trend in the agreement of natural frequencies and mode shapes between the experiment and FE simulation demonstrates that it is difficult to very accurately acquire higher order modes from either the measurements or the FE models due to the more complex response mechanism and FE modelling errors.
• The developed models can serve for a more precise dynamic response prediction and safety evaluation of the bridge in different severe circumstances such as earthquakes and traffic loading.

ACKNOWLEDGMENTS

The authors would like to thank the New Zealand Earthquake Commission (EQC) Research Foundation for financial support for this research (Grant No. UNI/578), and the New Zealand Transport Agency (NZTA) for providing access to the bridge. Piotr Omenzetter’s work within the LRF Centre for Safety and Reliability Engineering at the University of Aberdeen is supported by Lloyd’s Register Foundation. The Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research. Ge-Wei Chen would like to thank the China Scholarship Council (CSC) for the financial support for doctoral study (grant no. 2011637065).

REFERENCES

ANSYS (2012). ANSYS Version 13.0, Mechanical APDL.