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ASSESSMENT OF A MULTIPLE-SPAN BRIDGE BY DYNAMIC TESTING, IN-SITU MONITORING AND NUMERICAL MODELLING

Xinghua Chen[1], Piotr Omenzetter[2(*)], Sherif Beskhyroun[1]

[1]Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand
[2]The LRF Centre for Safety and Reliability Engineering, University of Aberdeen, Aberdeen, UK
[(*)]*Email:* piotr.omenzetter@abdn.ac.uk

ABSTRACT

The structural condition assessment of highway bridges is largely based on the visual observations described by the subjective indices, and it is necessary to develop a methodology for accurate and reliable condition assessment of in-service bridges. In this paper, an approach to condition assessment of in-service bridges making use of dynamic testing, in-situ monitoring and analytical and/or numerical simulations is proposed and applied to Newmarket Viaduct, a 700m long, 12-span bridge located in Auckland, New Zealand. Both ambient dynamic tests in two states and structural health monitoring data measured on the Newmarket Viaduct are reported and analysed. A finite element model of the bridge is successfully verified by using the natural frequencies and mode shapes extracted from the measured data. In the future work, monitoring data interpretation will be undertaken with the aim of inferring the state and condition of a structure. Also, the FE model for the structure calibrated and refined using the various types of field testing and monitoring or measurements data will be used in structural analysis simulations, yielding more realistic results.

Keywords: bridge, dynamic testing, model updating, structural health monitoring

INTRODUCTION

Highway bridges, as critical components of any nation's transportation network infrastructure, are normally designed to have a long life span. In order to reach a sustainable development of the society, it is of great importance that the huge investments that are made in the infrastructure can be utilized during the entire lifetime of the structures. However, because of increasing traffic volumes and speeds, tougher environments and accelerated aging of materials, bridges nowadays begin to deteriorate quicker that it was once the case. Consequently, the structural capacity of an existing bridge is typically less than the structural capacity of a new structure designed to the same targets. Even if the deterioration does not lead to the direct failure of a bridge, it may weaken the structure, making it more vulnerable to dynamic loadings resulting from earthquakes, winds and moving vehicles and decreasing its load bearing capacity. Failures of some major bridges, arising from such issues as lack of inspection and maintenance, or natural and man-made disasters, have been widely reported (Shepherd and Frost, 1995; Wang et al, 2002). Therefore, it is important to determine the integrity of a structure in terms of its level of safety and reliability for daily use in order to prevent catastrophic events (Chang et al, 2003). This has drawn increasing attentions recently, and many bridge engineers and researchers in the world are now faced with the challenge to develop innovative solutions to enhance the performance level or extend the service life of existing bridges. Condition assessment of important bridges plays an important role so that early identification and localization of any potential problems can be made.

For structural condition assessment, the finite element (FE) method has become a powerful tool (Xia and Brownjohn, 2004; Lin et al, 2006; Mottershead et al, 2011). FE modelling of bridges is now routinely undertaken in the normal design process of new structures and in the assessment of existing structures. With advances in numerical modelling, it is generally expected that FE models based on technical design data, as-built drawings, on-site geometric survey and engineering judgment can reliably simulate both static and dynamic structural behaviour. However, traditional condition assessment methods are typically based on such idealized analytical model, which lack knowledge of the existing states and actual performance of the as-built bridge structures. This approach may not permit an accurate evaluation of the bridge condition because it takes no consideration of the existing states and actual behaviour of the as-built bridge structures.

Currently, condition assessment of existing structures relies heavily on visual inspection and simple non-destructive testing, which suffer from being highly subjective and inaccurate and are not suitable for the increasing development of bridge structures (Phares et al, 2003). Therefore, it is necessary to found an effective method to evaluate the condition of bridge structures. The performance and structural behaviour of highway bridges should be determined using field testing and monitoring or measurements, and FE analyses should be compared to the experimental data (Brownjohn et al, 2003).

With the development of sensor technology, structural health monitoring (SHM) techniques have become a suitable choice for more accurate assessment of structural performance in a non-destructive manner (Peil, 2005; Ko and Ni, 2005; Gentile and Saisi, 2011; Okasha and Frangopol, 2012). SHM provide an effective way of characterizing a bridge structure for its static and dynamic properties. SHM systems automatically measure various loads and other actions imposed on a structure, its responses and condition (e.g. corrosion). Although it is premature to assume that SHM will soon, if ever, completely replace visual inspections, those technologies provide a way to alleviate the subjectivity of visual-inspection-based asset management and some other problems such as high manpower demands, insufficient frequency, inaccessibility of critical structural elements and lack of information on actual loading and responses. SHM can provide indispensable data for calibration of any analytical or numerical models for realistic outcomes.

The recently constructed Newmarket Viaduct in Auckland is a critical link in the New Zealand state highway network. The construction created a research opportunity to evaluate performance of such structures. A continuous health monitoring system was designed and installed on the bridge collecting data on structural responses, including strains, acceleration, displacements and temperatures. Also, two one-off, three day-long modal testing campaigns using some 50 wireless sensors in multiple setups were carried out under service conditions and ambient vibrations to collect data to map with high density 3D mode shapes of the bridge at two different construction stages.

In this paper, a comprehensive framework for condition assessment, which is based on dynamic testing, in-situ monitoring and analytical and/or numerical simulations, is proposed. The overall aim is to realize meaningful interpretation of monitoring or testing data in order to infer the state and condition of the structure. Also, the FE models for the structure calibrated and refined using the various types of field testing and monitoring or measurements data will finally be used in numerical simulations, yielding more realistic results.

The outline of the paper is as follows. The proposed method for condition assessment is first described. Then the case study bridge, Newmarket Viaduct, is introduced and described. The following parts provide descriptions of the two ambient tests conducted in two different construction stages, bridge monitoring system, and FE model. An overview of available data and results of dynamic testing, monitoring, numerical analysis and laboratory investigations on material properties are also provided in these parts. Based on these data, in the next section the condition assessment is described in detail. Finally, conclusions and further research are given in the final section.

GENERAL FRAMEWORK FOR CONDITION ASSESSMENT

In the proposed framework (Figure 1), for a given bridge structure, various types of data, such as from long-term, continuous monitoring, one-off or periodic testing and monitoring, and laboratory tests, can be used to perform advanced condition assessment. Different data interpretation methods are proposed to identify the actual behaviour of bridge at certain points in time from the various types of data and then compare the relevant performance parameters to ascertain the trends of variation over time. One way to assess a structure is to observe changes in vibration characteristics such as natural frequencies and mode shapes of bridges. Those changes, if properly identified and classified, can provide a viable means for damage detection of the structure.

Also, FE analysis and updating is included is in proposed method, which provides a powerful tool for enhanced condition assessment. An initial FE model, constructed according to design drawings and specifications, is required at first. The various types of data are used to calibrate, or update, the initial FE model. The model not only accounts for structural geometry and stiffness (Young's moduli of materials), but also for creep and shrinkage in concrete, relaxation in steel, and thermal expansion of materials. Furthermore, in a considerably more challenging process modal parameters (natural frequencies and mode shapes) from accelerations, time histories of strains and deflections due to creep and shrinkage, and strains and deflections due to temperature changes, all collected by the SHM system, are used to calibrate, or update, the FE model of the structure. Based on the monitoring and testing data and the updated model, condition assessment of main components or the entire bridge at any time will be conducted, which will aid the bridge maintenance decision-making process.

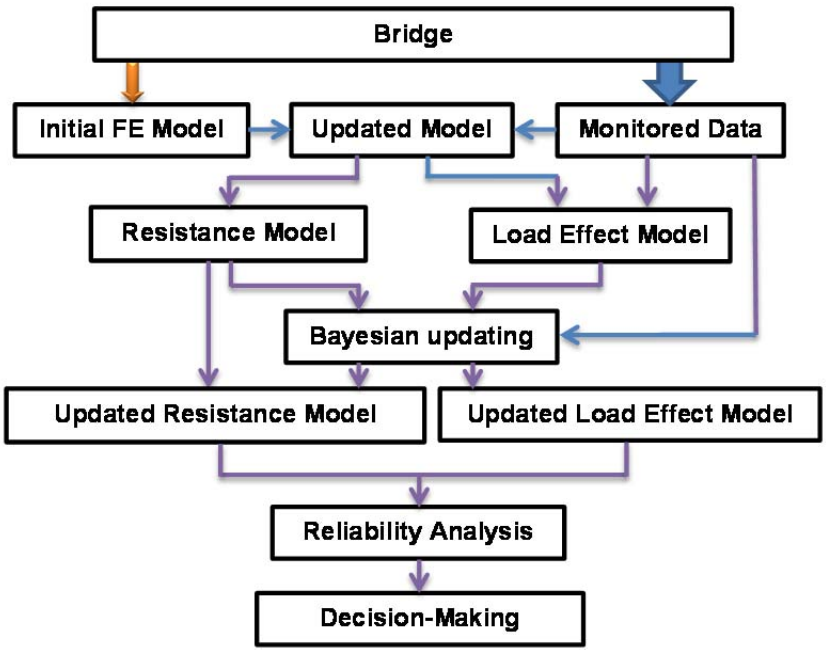


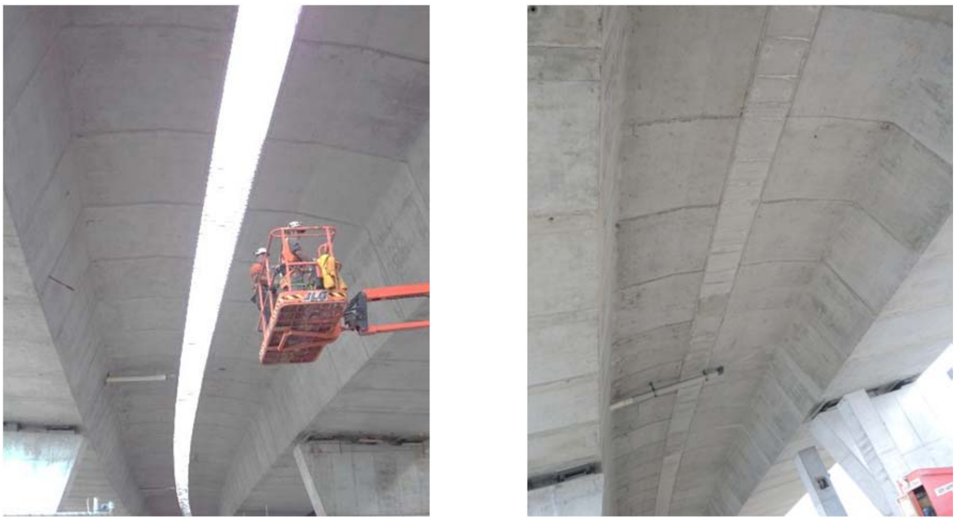
Fig. 1 Framework for bridge condition and performance assessment using SHM data

DESCRIPTION OF THE BRIDGE

Newmarket Viaduct, recently constructed in Auckland, is one of the major and most important bridges within the New Zealand road network. Figure 2 shows a side view of the bridge. Newmarket Viaduct 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. The Northbound and Southbound Bridges are joined together via a cast in-situ concrete 'stitch'. Now, both bridges are opened to traffic.

Fig. 2 Side view of 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. The deck of the bridge contains a total of 468 precast box-girder segments and was constructed using the 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 3 shows images of the bridge soffit before and after casting of the 'stitch'.



(a) (b)

Fig. 3 The soffit of Northbound and Southbound Bridges a) before and b) after casting of in-situ concrete 'stitch'.

AMBIENT TESTS OF THE BRIDGE

One-off dynamic testing is an important part of bridge assessment. Ambient tests were planed so that the bridge dynamic behaviour, i.e., frequencies and mode shapes, could be investigated under ambient vibrations. The specific objectives were to investigate the actual dynamic responses, i.e., acceleration under operational traffic loading. Furthermore, the results of the field tests were used to validate the FE modelling.

Two extensive one-off ambient vibration test campaigns were carried out on Newmarket Viaduct to determine the actual bridge dynamic characteristics at a construction stage and for the final state. 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 completion and after casting of the ‘stitch’, covering both bridges (the Southbound Bridge and the Northbound Bridge). For full details of the testing including test locations please refer to Chen et al (2013). Figure 4 shows accelerometers placed inside the girder during testing.

The data processing and modal parameter identification were carried out using an in-house system identification toolbox written in MATLAB (Beskhyroun, 2011). The enhanced frequency domain decomposition (EFDD) method procedures (Jacobsen et al, 2007) 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. Several vertical and transverse vibration modes were identified in the frequency range 0-10Hz (Table 1). Figure 5 shows selected vertical and transverse mode shapes identified. The FE model results were compared with those obtained from experimental measurements and showed very good correlation.

Fig. 4 Accelerometers inside bridge girder in Test 2.

SHM SYSTEM

SHM offers opportunities to more accurately assess the structural safety, repair and detect the structural damage of bridge structures. The long term SHM system installed in Newmarket Viaduct comprises 20 vibrating wire strain gauges (VWSG) that also measure temperature, 42 embedded temperature sensors, four baseline systems measuring deflections, and two external temperature and humidity sensors, one inside and another outside the girder. Four strain gauges are embedded in concrete in each of the following five cross-sections where sagging or hogging moments have the largest values: in the middle of Span 8 and 9, close to their common pier and at both ends of the two spans. 42 temperature sensors are located in the middle of Span 9 and are spread evenly in both webs along their height; additional sensors are installed across the webs and in the top and bottom slab. In Span 8 and 9 spans, baseline systems for measuring deflections are also installed. Data from these sensors is sampled at 10min intervals with the intention to measure static and slowly-varying responses due to creep, shrinkage and temperature variations. Communication with the data logger for data download is via a wireless modem over a cellular telephone network. SHM data collection on Newmarket Viaduct started in 2010 and it is planned to be continued for the foreseeable future. Installation of six uniaxial accelerometers is planned in near future to complement the aforementioned measurements with dynamic responses in the vertical and horizontal directions due to traffic.

The following quantities are or will be monitored on Newmarket Viaduct and will be used in structural assessment:

a) Strains and deflections in selected critical sections and spans of the girder.
b) Accelerations of key sections for structural natural frequency, damping and mode shape estimation.
c) Ambient temperature and humidity and structural temperature.

As an example, Figure 5 present the concrete strain responses from four sensors located in the section close to a pier of Span 8 and ambient temperatures. It can be seen that the concrete strain (negative values in the figure) increases rapidly during posttensioning and during the first year, with smaller strain changes as the concrete age increases. Comparing the strains to the ambient temperature, it can be seen that concrete strains fluctuate largely as dictated by the ambient temperature. The concrete compressive strain increases during the summer seasons and decreases during the winter seasons.

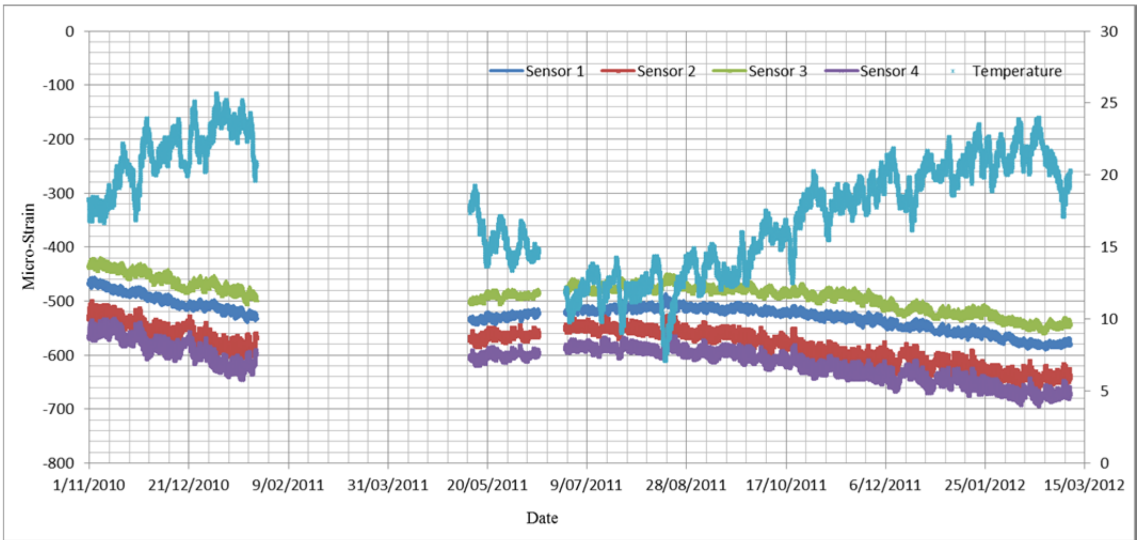


Fig. 5 Time histories of concrete strains in an instrumented cross-section and ambient temperature

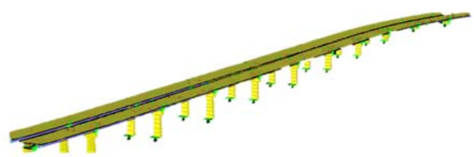
NEMERICAL MODELLING

Throughout this study, specialised finite element software CSiBridge has been employed for modelling the structure. The superstructure was represented using solid elements, piers and pier caps were modelled using beam elements, and expansion joints and bearings using link elements. Fixed boundary conditions were specified at the base of the piers. The 3D FE models were developed referring the two dynamic testing in different states are show in Figure 6.

In order to model the bridge, it is necessary to measure a number of material properties of the concrete used in construction. Twenty concrete 100×200mm cylinder specimens were secured on site during construction. Six of these were cast for the purpose of measuring compressive strength and elastic modulus, but authors' own results were amply supplemented by the analogous tests conducted by the contractor. Based on the concrete test results (Chen et al, 2012), in the finite element analysis concrete in bridge girder was assumed to have compressive strength of 60MPa, modulus of elasticity of 30GPa and a density of 2550kg/m^3. The remaining cylinders were used for creep and shrinkage tests. For full details of the testing please refer to Chen etc. (2012).

Frequency analysis of the FE model was conducted and close agreement was obtained with the dynamic field test results. In Figure 7 and Table 1, the mode shapes and frequency values of vibration of the bridge in two tests are given, respectively.

(a)



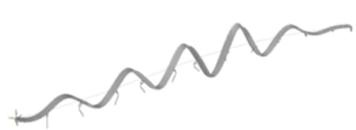
(b)

Fig. 6 3D FE model of Northbound and Southbound Bridges a) before and b) after casting of in-situ concrete 'stitch'.

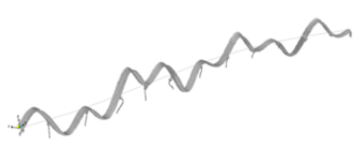
F_Mode=2.11Hz

F_Mode= 2.67Hz

F_Mode=3.95Hz



F_Mode=2.15Hz



F_Mode= 2.88Hz

F_Mode=6.88Hz

Fig. 7 Selected mode shapes of the bridge obtained by numerical analysis for Test 1.

Table 1 Comparison of dynamic characteristics calculated from the measured accelerations and FE model of the Newmarket Viaduct in Test 1 and Test 2.

Test 1				Test 2		
Mode	**Type of Mode**	**EFDD/Hz**	**FEM/Hz**	**Mode**	**Type of Mode**	**EFDD/Hz**
Mode 1	Transverse	1.64	1.65	Mode 1	Vertical	2.03
Mode 2	Transverse	2.11	2.11	Mode 2	Transverse	2.14
Mode 3	Vertical	2.15	2.15	Mode 3	Vertical	2.34
Mode 4	Vertical	2.42	2.44	Mode 4	Vertical	2.54
Mode 5	Vertical	2.62	2.64	Mode 5	Vertical	2.81
Mode 6	Transverse	2.73	2.67	Mode 6	Vertical	3.12
Mode 7	Vertical	2.89	2.88	Mode 7	Vertical	3.32
Mode 8	Vertical	3.20	3.16	Mode 8	Transverse	3.44
Mode 9	Vertical	3.52	3.40	Mode 9	Vertical	3.67
Mode 10	Transverse	3.63	3.95	Mode 10	Vertical	3.83
Mode 11	Vertical	3.75	3.70	Mode 11	Vertical	4.30
Mode 12	Vertical	4.20	4.22	Mode 12	Vertical	7.46
Mode 13	Vertical	6.88	6.88			

CONDITION ASSESSMENT

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 the concrete ‘stitch’ between two bridges, the following observations can be made. The frequencies of the first two transverse modes have increased from 1.64Hz to 2.14Hz and from 2.11Hz to 3.44Hz, respectively. The frequencies of the first two vertical modes have decreased, from 2.15Hz to 2.03Hz and from 2.42Hz to 2.34Hz, respectively. After the casting of the ‘stitch’, the two bridges work as one whole structure, thus the frequency changes were caused by the two bridges interacting with each other.

Based on the permanent dynamic and strain monitoring data, it is proposed to use different structural identification methods to identify the actual behaviour of Newmarket Viaduct at certain points in time and then compare parameters to ascertain the trends of variation over time. Figure 8 presents the concrete strain responses from the same sensors showed previously in Figure 5 but on the days one year apart, November 29 2011 and 2012, which are the days of the two dynamic tests. It can be seen that the concrete strain increased from 2011 to 2012.

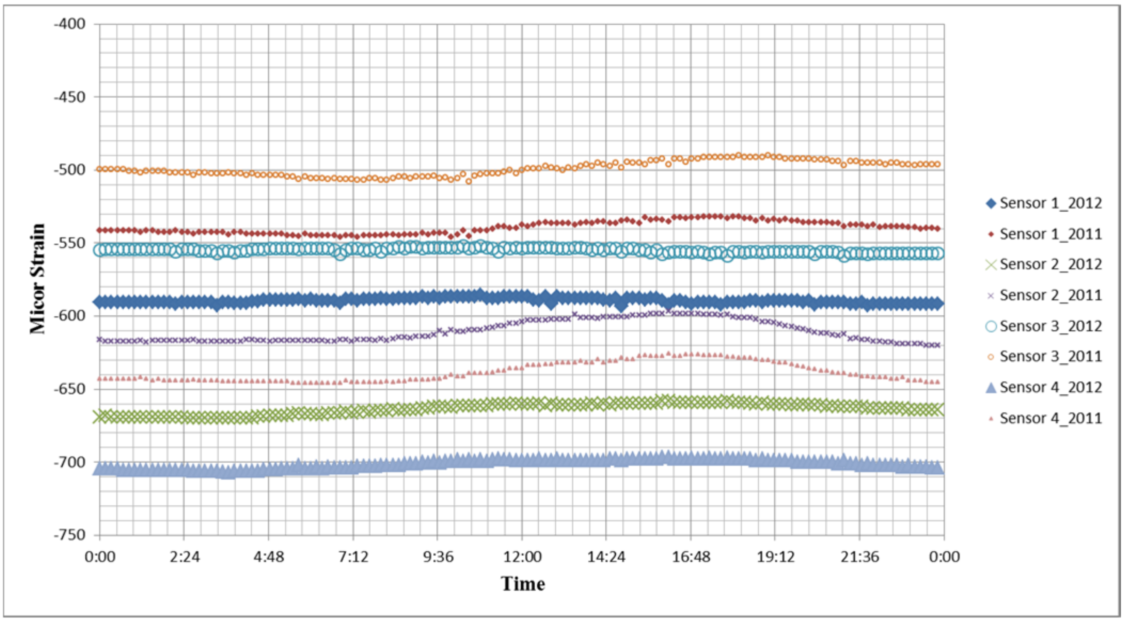


Fig. 8 Comparison of concrete strains in an instrumented cross-section in 2011 and 2012

CONCLUSIONS AND FUTURE RESEARCH

In this paper, an approach for integrating various types of data, including dynamic test data, long term monitoring data and laboratory test data, in a condition assessment framework for an in-service bridge is proposed. In the framework, advanced modelling tools and techniques are used for the structural analysis. The long term monitoring data, field testing and laboratory data will be used to provide a more realistic assessment.

Followed by the framework, this paper also presents some preliminary results for a 12-span viaduct. Two dynamic tests have been performed on the bridge in two different construction stages (before and after the two bridges making up the viaduct were joined 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, whereas the frequencies of the first two vertical modes decreased. From the analysis of monitoring data measured on the bridge, the concrete strains in one cross-section have also increased.

Based on the permanent monitoring data, it is proposed to use different structural identification methods to assess the actual behaviour of Newmarket Viaduct at certain points in time and then compare the parameters to ascertain the trends of variation over time.

Finite element models to be used for assessing the performance of the bridge cannot be used without calibrating. The initial model does not account for inherent variability of material properties and time-dependent stiffness changes, therefore, the initial FE model will be calibrated using ambient vibration test results. The model calibration is aimed to match the frequencies and mode shapes obtained via FE analysis with their experimental counterparts. To calibrate the FE model, a parametric study will be first carried out and the influential parameters identified. The most influential parameters to structural dynamic characteristics will be selected as the main calibration parameters. The FE model calibration will be carried out by adjusting those selected parameters until good matches in the natural frequencies and modal shapes are observed.

In the future, available data from laboratory tests will also be used in a Bayesian updating process to produce posterior probability distribution of concrete Young's modulus and creep and shrinkage coefficients (Chen et al, 2012). Furthermore, in a considerably more challenging process modal parameters (natural frequencies and mode shapes) from accelerations, time histories of strains and deflections due to creep and shrinkage, and strains and deflections due to temperature changes, all collected by the SHM system, will be used to calibrate, or update, the FE model of the structure. Novel approaches to updating using soft-computing methods (Shabbir and Omenzetter, 2012) will be tried for the first time for an updating problem of this size.

The refined finite element model will then be used to evaluate the load rating of the current condition of Newmarket Viaduct according to proposed design loads. The numerical model will also be a fundamental tool to understand the effect of the bridge supports on its mechanical properties to be studied in future. The framework presented in this paper is believed to be a practical tool for establishing rational, continuous and accurate decision support system for managing such bridge structures.

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