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Experimental investigation into amplitude-dependent modal properties of an eleven-span motorway bridge

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ABSTRACT

This paper examines experimentally the effect of forcing and response amplitude on the variability of modal parameters of a bridge. An eleven-span prestressed concrete motorway off-ramp bridge was subjected to multiple dynamic tests with varying excitation levels by using eccentric mass shakers exerting forces in the vertical and lateral direction. The frequency sweeping technique with small increment steps in the vicinity of resonant frequencies was employed to construct frequency response functions at different shaking levels from which the natural frequencies, damping ratios and mode shapes were identified for several vertical, mixed vertical–torsional and lateral modes. Softening dynamic force–displacement relationships were observed for all the modes, and the natural frequencies showed clear and consistent decreasing trends with increasing response amplitude. Modal damping ratios initially increased with increasing response amplitude, but later, for the modes where experimental data were available, stabilised at elevated levels. A finite element (FE) model of the bridge was also created and the experimental modal properties compared to the numerical ones. A good agreement was generally noticed for the lower modes but the higher modes had more error. The FE model was used to assess the likely levels of structural damage that would have a similar effect on the natural frequencies as the amplitude dependence. One numerical damage scenario indicated that a reduction of 20% of stiffness in the middle of the main span would cause larger frequency shifts of some modes but amplitude dependent effects will dominate in other modes. Another numerical damage scenario was a reduction by 50% of stiffness at the bottom of the highest pier, and it was shown this type of damage would result in only one third of the frequency drop caused by the amplitude effects in a single, most affected mode.

1. Introduction

Bridge structures play a central role in modern economy, and many of them continue to be in service despite aging and the associated potential for damage accumulation. Consequently, efficient monitoring of the health of these structural systems becomes increasingly important. The commonly used methods for structural evaluation of bridges include visual inspections and localized experimental methods, e.g., acoustic emission, X-ray inspection, and ultrasonic and eddy current scanning [1–3]. However, many of these methods can be costly and time consuming, and require knowledge of, and direct access to, the structural problem location. The need for alternative means to assess the structural condition has led to the development of various monitoring techniques including vibration-based structure health monitoring (VBSHM) methods [4–7]. These are based on the well-known principle that structural damage changes the mechanical properties, such as stiffness, and thereby alters the dynamics of the structure and reveals itself in the measured dynamic responses and characteristics (e.g. modal properties). Despite the intuitive premise for the VBSHM methods, one of the major hindrances in their practical applications is that dynamic characteristics of a structure will often be significantly affected by changing environmental conditions (such as temperature) [8], and will also depend on response amplitude (directly related to the external excitation levels) [9,10], which must be taken into account in VBSHM approaches. Thus, sound understanding of the variability in dynamic properties of a bridge structure due to typical environmental and loading level variations is required for using the VBSHM techniques reliably to discern the changes caused by actual structural damage or deterioration. Abundant literature concerned with the effects of temperature on modal parameters, quantitative relationships between temperature and modal properties, and data normalization to account for

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environmental variability exists [11–17]. However, comprehensive explorations of the influence of excitation force level on the variability in dynamic characteristics of bridge structures are limited, because this operational variable is difficult to precisely measure. In fact, concrete structures generally behave at least weakly nonlinearly even at moderate excitation levels due to the nature of reinforced concrete stress–strain relationship. With the increase in response amplitude, structural stiffness tends to deteriorate because of the material and structural nonlinearities and this stiffness reduction can be observed as a decrease in natural frequencies. Damping, on the other hand, represents energy dissipation in a vibrating structure, and it plays a significant role in reducing structural response to a dynamic excitation near resonance. Experimental determination is currently the only reliable way of quantifying damping [18], since an analytical evaluation from first principles is extremely difficult, if at all possible, due to the complicated damping mechanisms. A large volume of ambient excitation data for bridge structures have been collected and analysed by many researchers. However, Ren et al. [19] pointed out that the applicability of damping ratios identified through ambient vibration testing requires further evaluation using alternative identification techniques and other dynamic tests with large vibration amplitudes. Previous tests conducted under varying magnitude of excitation often reveal that both natural frequency and damping are strongly dependent on the magnitude of response even though the structure may behave elastically [20–27]. Zhang et al. [28] found that the natural frequencies of a cable-stayed bridge can exhibit up to 1% variation within a day due to different vibration intensity under varying traffic conditions. Damping ratios were also reported as sensitive to the vibration amplitude, especially when the deck vibration exceeded a certain level. Cross et al. [29] reported that the first five modal frequencies of a deck had a tendency to decrease with the increased root-mean-square values of the vertical and lateral deck accelerations based on the analysis of three years of monitoring data of the Tamar suspension bridge. Fujino et al. [30] observed that the fundamental frequency of a suspension bridge reduced as the wind speed increased but a contrary trend was observed for damping ratio. Farrar et al. [31] noted there were significant changes in the damping ratios correlated with excitation amplitude in their tests on the Alamosa Canyon bridge. Ülker-Kaustell and Karoumi [32] found the first vertical bending mode natural frequency declined linearly with the increase of the vibrational amplitude in a ballasted, single span, concrete–steel composite railway bridge by analysing the free vibration response after a freight train passage. An opposite trend for the equivalent viscous modal damping ratio was observed. Gomez et al. [33] showed that in general larger earthquake intensities resulted in reduced vibration frequencies and higher damping ratios by analysing six seismic records of a three-span curved highway bridge. Although these observations help in gaining some insights into the influence of the excitation and response level on the variability in the dynamic characteristics of bridges, a precise and quantitative understanding of the amplitude-dependent dynamic properties of bridge structures has not been achieved yet due to the relative lack of adequate response data under broadly varying force excitation levels, especially for multiple-span highway or motorway concrete bridges, many of which have been equipped with dynamic monitoring systems in recent years [34–36].

The objective and contribution of this paper is to provide further insights into the amplitude dependency of the natural frequencies and viscous modal damping ratios of bridge structures in a broad vibration intensity range realised via forced vibration testing experiments. An eleven-span, post-tensioned concrete motorway bridge was tested as the case study. Frequency sweeping excitation at several forcing levels applied by rotating mass shakers was utilized to excite the bridge in the vertical and lateral direction. A series of frequency response functions (FRFs) at different levels of excitation were constructed, and natural frequencies and damping ratios were identified from these FRF curves for several vertical, mixed vertical–torsional and lateral modes. Softening relationships between the amplitude of dynamic forcing and response were observed. A consistent trend of decreasing modal frequencies with increasing forcing and response level was also clear for all the identified modes. Damping, on the other hand, initially increased, but later stabilised for those modes where testing continued into large response amplitude range. Quantitative relationships between modal parameters and response amplitude were obtained from available experimental data and used to describe the amplitude-dependent behaviour of the bridge in the tested amplitude ranges. The measured modal properties at the lowest forcing level were compared with the numerical results obtained from a finite element (FE) model and an overall good agreement was achieved, although higher modal frequencies and shapes showed larger differences. The FE model was then used for simulating two damage scenarios and comparing the frequency shifts due to damage and response amplitude effects. It was found that that even significant damage may cause modal frequency variability less noticeable than that due to the response level effects. The paper is organized as follows. Firstly, the bridge and the experimental programme are described, and then the results of modal system identification and their analyses and discussions are presented. This is followed by a description of the FE model and comparison of the numerical and experimental results. Finally, the numerical simulations of damage scenarios are conducted and observations about frequency shifts due to damage versus response amplitude are discussed. A set of conclusions rounds up the paper.

2. Description of the bridge

The structure under investigation is the Nelson St. off-ramp bridge located on the southern fringe of the Central Business District of Auckland, New Zealand, at a confluence of three major motorways. The bridge was built in 1976 and used for a number of years thereafter. Currently, it is closed to traffic and kept as a redundant link in the motorway junction for possible emergency and regular future uses. The closure of the bridge created an excellent opportunity for a longer, undisturbed and comprehensive testing campaign, a part of which is the topic of this paper. Two views of the bridge appear in Fig. 1, while Fig. 2 is a sketch explaining the overall structural form and arrangement and showing major dimensions. The bridge has a horizontal as well as vertical curvature. Its total length is 272 m and it comprises 11 post-tensioned concrete spans. The main span is 40 m long and the remaining spans vary in length between 18 and 26 m, with the majority of them 24 m long. The superstructure was built of a total of 137 precast single-cell box girder segments delivered to the site, placed in their final position on movable scaffolding and then post-tensioned. Two different precast cross-sections of heights 1.73 m and 1.09 m, respectively, were used and are shown in Fig. 3. The cantilevered extremities of the girder upper flange were precast separately and connected to the box section using reinforcement bars protruding from the box section. Steel guardrails were bolted to the cantilever slab of the girder on both sides along the whole length of the bridge, while a concrete channel was installed along one side of the girder cantilever slab for rainwater drainage. A 40 mm thick layer of mixed asphalt and crushed stone gravel or sand was used for the bridge roadway paving.

Ten solid octagonal piers of height between 4.27 and 14.43 m and the maximum width and thickness of 2.85 m and 1.42 m, respectively, provide intermediate supports (refer to Fig. 2 for pier