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Finite element modal analysis and vibration-waveforms in health inspection of old bridges

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ABSTRACT

The validity of using the finite element modal analysis in combination with the operational vibration-waveforms generated by vehicles to guide structural health monitoring observers in their inspection of old bridges is investigated in this work. A nondestructive vibration-based approach, operational response and waveform analysis (ORWA), is introduced and used in the process of validating the predictability of the finite element model. In ORWA, the frequency-domain response of a highway bridge is generated from the operating traffic load, and the structural response is visualized and used to develop a holistic view of the bridge's response to automobile loadings. By visualizing the response of the bridge, concrete cracking in the abutment and deck is correlated with certain types of structural motion and their corresponding frequencies. Significant excitation frequencies for this particular structure and loading are identified using a frequency-domain study of the vibration-waveforms generated by vehicle, and field results showed similarity with field impact tests conducted on the bridge. The finite element modal analysis of the original CAD drawings of the bridge in combination with the vibration-waveforms generated by vehicles spectrum has demonstrated realistic consistency with the findings of ORWA in showing the correlations between the physical damage areas on the bridge and the excited mode shapes of the operational loading that tend to cause these types of damage.

1. Introduction

Maintaining a safe and reliable civil infrastructure is of utmost importance to the national economy and the well-being of all citizens. With more than half of the 600,000 bridges in the United States built before 1975, areas of research related to bridge maintenance, inspection, and monitoring have received significant attention in recent years [1,2]. For example, in Iowa, especially, where 21% of the almost 25,000 bridges are structurally deficient and over 1000 bridges are more than 100 years old, the development of technologies related to the extension of bridge life is crucial to the state's economic growth [1]. Furthermore, since 1956, vehicle miles of travel in Iowa have increased by 176% [3], yet many bridges 50 years and older remain essentially the same structures as when first constructed.

Much of the latest research in the civil infrastructure health monitoring field is focused on dynamic testing and finite element model updating [4,5]. Many researchers focusing on vibration-based health monitoring have used changes in natural frequencies [6], modal analysis methods [7–9], and frequency response function methods [10–12] to detect, locate, and quantify damage. Dynamic testing of field structures has been completed using both forced excitation with an impact hammer [13–15] and shaker [8,16,17], as well as ambient or operational excitation, often using traffic as a source of vibration [18,19]. Finite element model updating with experimental modal parameters has also been investigated [20–24]. Many of the current dynamic tests are difficult to implement on aging field structures [2,5,25], are prone to error due to experimental noise and complicated boundary conditions [26], and are often too global to detect small, localized damage [27]. In addition, field studies using modal analyses have shown that changes in modal parameters due to damage are relatively small and can be overshadowed by changes in environmental parameters such as temperature [28].

Local health monitoring methods, such as those based on nondestructive manual testing, including ultrasonic, tapping, and imaging [26,29], have been very effective in locating damage in the

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areas where they are used. Their advantages could be maximized if the observers had prior knowledge about critical locations on the structures. This would save the observers a significant amount of time and make their testing plans more effective. Therefore, the existence of a finite element model of the bridge can be a very useful tool in guiding observers in their inspection process.

The aim of this paper is to investigate the possibility of using the finite element modal analysis of old highway bridges, with information from the initial CAD drawings of the bridges, as a qualitative tool in assisting bridge observers in identifying the locations of the critical high stress/strain zones on the bridges that are associated with certain frequencies caused by the vibration-waveforms generated by vehicle. Experimental data from a 60-year-old highway bridge using operational response and waveform analysis (ORWA) was used as a baseline for comparison with the finite element modal analysis findings. The paper details the experimental methods used to obtain operational response data for a single-span highway bridge and presents evidence of problematic structural motion caused by certain frequencies present in traffic loading. Actual, visible damage present on the bridge is shown and correlated with motion through the use of waveform analysis and then compared with finite element modal analysis findings.

1.1. *Description of field-tested bridge*

The bridge investigated (FHWA #31690) is a composite steel I-girder and concrete deck bridge with a single span of 18.6 m (61 ft) carrying Highway 1 over a small natural creek in Johnson County, Iowa (Fig. 1a). It was constructed in 1949 with two W33 × 130 exterior girders, two W36 × 150 interior girders, a 20.3 cm (8 in.) composite action concrete deck, and a diaphragm consisting of twelve C15 × 33.9 channel sections between all girders (Fig. 1b). One end of each girder is fixed with a pintle (notch protruding from the masonry plate through the bearing plate), and the other end rests on the abutment, serving as a roller. The abutments and wing walls are supported by 42 untreated timber piles, each 13.7 m (45 ft) in length. Although the structure was not rated structurally deficient during its last bridge inspection, it has been deemed functionally obsolete and received a sufficiency rating of 37/100, meaning it is intolerable and requires high-priority corrective action.

2. Materials and methods

2.1. *Operational response and waveform analysis (ORWA)*

Methodologies currently being used in the mechanical systems and machinery field have shown great success in accomplishing all five goals. They aim to detect, locate, and quantify damage and then correlate that damage with operational loading and provide a solution to the problematic structural motion [30–33]. However, their potential usage on large civil structures has been given very little attention.

ORWA can be summed up in four steps: (1) experimentally gathering operational response data, (2) visualizing structural motion across a large frequency spectrum, (3) determining the most significant excitation/response frequencies, and (4) correlating structural motion at significant frequencies with structural motion caused by operational excitation.

In this work, operational response at various parts of the structure was visualized using acceleration data that were manipulated to give an operating deflection shape (ODS), which is a technique used for visualization of the vibration pattern of a structure under real-life operating conditions. Unlike mode shapes, an ODS can be used to analyze the response of a structure under forces and complicated boundary conditions because it contains both forced and resonant vibration components. Operating deflection shapes are one way to obtain correlation between different points on the structure and are capable of indicating the points with the largest motion and specifying their directions. They can also provide very useful information regarding the dynamic characteristics of a structure and its components.

An ODS is essentially a column vector of transmissibilities. For experimental purposes, it is convenient to view transmissibility as a function of the cross and auto spectra, which can be readily obtained from most multi-channel data acquisition systems. The cross spectrum is the product of the Fourier spectrum of a measured response and the complex conjugate of the Fourier spectrum of a fixed reference response, as follows:

$$G_{xy}(\omega) = F_x(\omega)F_y^*(\omega) \tag{1}$$

The auto spectrum is the product of the Fourier spectrum of the fixed reference response and its complex conjugate as follows:

$$G_{yy}(\omega) = F_y(\omega)F_y^*(\omega) \tag{2}$$

Transmissibility is simply the ratio of the cross spectrum to the auto spectrum, which gives the motion of each roving response point normalized by the motion of the reference response point as follows:

$$T_{xy}(\omega) = G_{xy}(\omega)/G_{yy}(\omega) \tag{3}$$

An alternative parameter to transmissibility (and ODS) is the operating deflection shape-frequency response function (ODSFRF), which is calculated by replacing the magnitude of the cross spectrum with the square root of the magnitude of the response

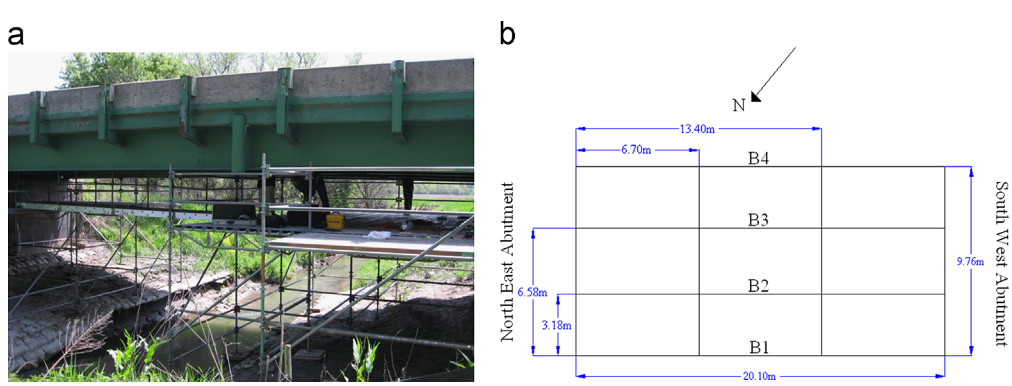

Fig. 1. (a) View of single-span composite steel I-girder and concrete deck field bridge (FHWA #31690) with scaffolding allowing access to the superstructure, (b) schematic of composite steel I-girder and concrete deck field bridge showing the four girders (B1, B2, B3, and B4), each having a length of 120.1 m, and the 12 diaphragms each having a length of 30.8 m.