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Modal-parameter identification and vibration-based damage detection of a damaged steel truss bridge

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ABSTRACT

Bridge damage detection has become increasingly important, but few related techniques have been tested in situ on real bridges. For this study, a field experiment was conducted on an actual simply supported steel truss bridge with four artificial damage scenarios applied sequentially. Preliminary results of modal-parameter identification and vibration-based damage detection are then presented. For each scenario, modal frequencies and mode shapes of the bridge were identified with high precision and accuracy using a stabilization diagram-aided multivariate autoregressive analysis of vehicle-excited bridge vibrations. Changes in the identified modal parameters attributable to the artificial damage were observed. For modal frequencies, they decreased as damage causing high stress redistribution was applied, signifying a global stiffness loss. For mode shapes, both symmetric and anti-symmetric ones were distorted when the damage was applied asymmetrically, but no distortion was observed when damage was applied symmetrically. Moreover, a damage detection approach in an order of feature extraction and discrimination was verified to be practicable if the damage-sensitive feature was properly selected. Multiple modal frequencies, specifically the first three and four modal frequencies, were effective features because they were highly sensitive not only to the presence but also to the severity of the artificial damage. Multiple modal assurance criteria (MAC) values and coordinate modal assurance criteria (COMAC) values were also effective features that were sensitive to damage scenarios examined herein if sufficient modes were considered. However, neither a single frequency nor a single MAC value was as effective as multiple ones because each was sensitive to certain specific damage scenarios only. When damping ratios were taken as features, most of their combinations were slightly sensitive to the asymmetric damage, but none of those combinations, neither single nor multiple damping ratios, was sensitive to the symmetric damage.

1. Introduction

For confronting issues of aging bridge infrastructure, bridge damage detection has become an important research and practical topic, especially for those developed countries in which numerous bridges were constructed during periods of rapid economic growth. Taking Japan as an example, it was estimated statistically in 2012 that those bridges having served over 50 years account for 9% of all bridges. In 10 years, those might reach 28%. In 20 years, those might exceed 53% [1]. To monitor the health condition of those aging bridges and those of certain important newly constructed bridges, pressing needs for inspection tasks aimed at detection of potential bridge damage continue to increase. Moreover, a huge number of urgent inspection tasks might be necessary when a natural disaster such as an earthquake or tsunami strikes.

One popular damage detection method uses structural vibration, based on the intuitive knowledge that damage can change a bridge's mechanical properties (e.g. stiffness, mass or energy dissipation mechanism). Therefore changes in its dynamic responses can be expected to occur in the time domain as well as dynamic characteristics (e.g. modal parameters or their relatives) in either modal or frequency domain [2,3]. Following this logic, damage can be detected by tracking the changes in those damage-sensitive features extracted from the structural vibration responses. Such methods are designated as vibration-based bridge damage detection (VBDD) methods. Compared with conventional visual inspections and non-destructive testing methods (NDT methods such as acoustic, ultrasonic, and radiography), VBDD methods provide the important benefit that they can evaluate the bridge health condition extensively even if the potential damage location is unknown *a priori* and even if the inspected parts are inaccessible [4,5].

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To investigate the VBDD technique effectiveness, field experiments conducted in situ on real bridges are important. They have high reference value because they are conducted in an environment that is most similar to those within which the VBDD systems will be operating. Such environments are generally not as well-controlled as those in numerical simulations and laboratories. However, most existing studies examine these VBDD techniques using numerical simulations (e.g. [6,7]) and laboratory experiments (e.g. [8–11]). A few reports describe their practical validity for actual bridges, which are likely to be subject to budget limitations and service conditions that prevent the relevant authorities from granting permission to apply damage to the bridge. Notable field damage experiments conducted in situ on real bridges include those on the I-40 Bridge [12,13], the Alamosa Canyon Bridge [13], the Z24 Bridge [14,15], the Dogna Bridge [16,17], and others [18–21].

From the acquired vibration data, one aims to extract damage-sensitive features and then to discriminate among features from the damaged and undamaged bridges quantitatively. The former procedure can be designated as feature extraction, whereas the latter can be regarded as feature discrimination [22]. A damage-sensitive feature is a certain quantity that presumably varies with the bridge health condition, as sensitively as possible, and is therefore capable of indicating the presence of bridge damage. Various damage-sensitive features have been presented in the technical literature related to VBDD, many of which are summarized systematically in review works by Carden and Fanning [3] and by Fan and Qiao [5], and in a book by Farrar and Worden [22]. Among those features, modal parameters received researchers' interest early, as early as the 1970s [23], because they are the physical quantities dependent on the structural stiffness [24]. Being studied for over three decades, the modal parameters serve as damage-sensitive features that reportedly present several limitations for application to real-world structures. One primary limitation is the low sensitivity of the parameters of lower modes to local damage, implying that these features might work effectively in limited cases involving very precise measurements or severe damage. It may be argued that such severe damage could be detected by conventional visual inspections, but VBDD are still superior to the visual inspections in several aspects. First, vibration-based methods do not require access to every component of interest. It is efficient when there are a great number of structural members and when some of them are hardly accessible. Second, the vibration-based methods can be performed real time and automatically while the visual inspections cannot. Considering those good aspects, in practical situation, the proposed methodology can be used to complement the conventional visual inspections. Let us take a valuable case for example. A fracture of a cross member was reported in a truss bridge in Japan in 2007 [25]. This fracture was located beneath the concrete deck and hardly accessible, making regular visual inspections fail to find it. To find a fracture like this on time, vibration-based methods can be complement tools.

Following the feature extraction procedure is feature discrimination, i.e. discrimination between features extracted from damaged and undamaged bridges so that the existence of damage can be detected. For civil infrastructure such as bridges, there are few measurement samples from damaged structures. In addition, those samples are expected to be very sparse in terms of sensor allocation and damage type. In relation to these practical difficulties, outlier detection (or novelty detection in the machine learning field) can be an appropriate tool for feature discrimination. One treats the observations collected in the undamaged condition as a reference dataset (or training dataset in the machine learning field) and tests if a candidate observation, either from a damaged or undamaged condition, is an outlier: if yes, it implies a damaged condition of the bridge, and vice versa [22,26]. Outlier detection is believed to work well at least for the first level, arguably the most important level, of the whole damage identification hierarchy discussed by Rytter [27]: damage detection (detecting the existence of damage), localization (locating the damage), assessment (identifying the severity of the damage), and prognosis (estimating the remaining life of the structure).

In considering the limited number of practical cases, we conducted a field experiment on an actual simply supported steel Warren-truss bridge in Japan with four artificial damage scenarios applied sequentially: a half cut in a vertical tension member at the midspan, a full cut in that member, a recovery of the cut member, and a full cut in a vertical tension member at the 5/8th-span. In the field experiment, excitement of the bridge economically, reliably, and rapidly is an important technical issue. For small-span and medium-span bridges such as the target bridge in this study, which form the major portion of bridge infrastructure, daily traffic is dominant in comparison to ambient vibrations induced by wind and ground vibrations [28,29]. For this reason, a passing recreational vehicle serves to excite the bridge. Vehicle-induced bridge vibrations are recorded for following analyses. This experiment (designated hereinafter as the field damage experiment) was able to serve as a benchmark for those bridges that are of similar type and which are vulnerable to similar damage scenarios.

The objective of this paper is first to summarize the modal parameters identified from the experiment and secondly to examine the practicality of a damage-detection approach in the order of feature extraction and discrimination. Both univariate and multivariate features are examined. The former can be a modal frequency, damping ratio, or modal assurance criteria (MAC) value of a specific mode. The latter can be modal frequencies, damping ratios, or MAC values of a couple of modes. Not only the feasibility but also the sensitivity of those features was investigated in this study. This paper is organized as follows. Section 2 provides detailed descriptions of the field damage experiment. Section 3 presents a brief description of the damage-detection procedures. Herein, various combinations of modal parameters identified by multivariate autoregressive (AR) time-series models are considered as damage-sensitive features. The features extracted from damaged and undamaged bridges are discriminated using outlier analysis. Section 4 presents the identified modal parameters and the damage-detection results, followed by several concluding remarks related to the implication and limitation of the damage detection approach in practical applications in Section 5.

2. Field experiment

The target bridge, vehicle, artificial damage scenarios, sensor layout and test types applied in the field experiment are described as follows.

2.1. Bridge and vehicle

The target bridge was a simply-supported through-type steel Warren truss bridge, as presented in Fig. 1. It has 59.2 m in span length, 8.2 m maximum height, and 3.6 m width, designed for a single lane. The bridge was constructed in 1959 and was slated for removal after a replacement bridge was opened to traffic in 2012. Before its removal, the bridge was allowed an experiment with artificial damage. During the experiment, the bridge had been closed to traffic. No other vehicle aside from the test vehicle was allowed.

The vehicle used for experiments was a two-axle recreation vehicle (Serena model; Nissan Motor Co. Ltd.) (Fig. 2) with total weight of about 21 kN. The fundamental frequencies of the vehicle were roughly identified in an independent drop test. They were