Damage detection of shear connectors in composite bridges under operational conditions

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Publication details
DAMAGE DETECTION OF SHEAR CONNECTORS IN COMPOSITE BRIDGES UNDER OPERATIONAL CONDITIONS

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ABSTRACT
This paper investigates if the relative displacement measurements from newly developed relative displacement sensors can be used to detect the damage of shear connectors in composite bridges under operational conditions. The relative displacements between slab and girders in composite bridges are measured when the bridge subjects to moving vehicle loads and used for condition monitoring. Continuous Wavelet Transform and Hilbert-Huang Transform are applied to analyze the measured dynamic responses and to identify the damage of shear connectors in the composite bridge model. To demonstrate the suitability of this new sensor and the corresponding time-frequency analysis algorithms in detecting the conditions of shear connectors, a laboratory composite bridge was built and tested. Accelerometers and LVDT displacement sensors are also used in the experimental tests together with the relative displacement sensors. Detection results with relative displacement sensors are compared with those from acceleration and deflection measurements. The performance and reliability of using direct relative displacement measurement in detecting the shear link conditions are demonstrated by experimental investigations.

KEYWORDS
Relative displacement sensor, damage detection, shear connectors, composite bridges, moving loads, time-frequency analysis.

INTRODUCTION
Damage detection is an important task in the areas of structural health monitoring and condition assessment of structures. The identification results will support the evaluation of structural integrity and load-carrying capacity. Composite structure represents a typical form for bridges on Australia highways. It consists of reinforced concrete (RC) slab and precast RC or steel girders. Shear connectors are used to link the slab and girders to increase the rigidity of composite bridges for uniform action under live traffic and other loadings. An example studied in (Nie and Cai 2003) indicated that damage of shear connectors would result in shear slippage between the slab and girder and therefore may result in the stiffness reduction up to 17% in a short span bridge.

Recently, an innovative relative displacement sensor (Li et al. 2013a) has been developed to track the shear slippage and failure of the shear connection in composite bridges by measuring the relative displacement between slab and girders. The accuracy of the developed relative displacement sensor has been validated. It has been demonstrated that the developed sensor gives accurate measurement of...
relative displacement between bridge girder and slab. It does not require a fixed reference point and can be directly installed on the target structure hence is easy to setup.

Time-frequency analysis methods, such as continuous wavelet transform (CWT) and Hilbert-Huang Transform (HHT), are popular and well adopted in structural health monitoring. The merits of time-frequency analysis methods lie in its ability to reflect both time and frequency domain information. Condition assessment of bridge structures is usually conducted from the measured responses under moving traffic which serves as the excitation to bridges (Li and Law 2012, Li et al. 2013b). It has been explored and demonstrated that CWT and HHT have the potentials to detect the damages in structures with measured displacement and acceleration responses under moving loads (Hester and Gonzalez 2012, Roveri and Carcaterra 2012).

DEVELOPMENT OF A RELATIVE DISPLACEMENT SENSOR

A relative displacement sensor has been developed based on the principle of Wheatstone bridge circuit and it can be used to measure the relative displacement between two locations (Li et al. 2013a). The main design idea of the relative displacement sensor will be briefly reviewed. Four strain gauges are stuck on a square component connecting two pads, which are used to fix the sensor on the testing structure, to construct a Wheatstone bridge circuit. The sensitive component of the sensor is a square metallic block around 20mm. Two pads at the ends are used to fix the sensor to structures with four 8mm diameter screws. The sensor measures shear distortion of the metal block owing to relative displacement of the two locations that the two end pads of the sensor are fixed to, which occurs along the horizontal direction. The output relative displacement is calibrated with measured strain, and then the developed sensor can output the displacement information from measured strains.

EXPERIMENTAL STUDIES ON DAMAGE DETECTION UNDER MOVING LOADS

Experimental Setup

A composite bridge model was constructed in the laboratory with a reinforced concrete slab supported on two steel girders. Sixteen identical shear connectors were mounted with equal spacing in each girder to link the slab and steel girders. The bridge model was located on two steel frames which were fixed to the laboratory strong floor as shown in Figure 1. The slab constructed with Grade 40 concrete was connected to two 150UB14 universal steel girders by shear connectors. The design of shear connectors allows for simulation of the failure of specific shear links as well as for resetting to the undamaged state. Therefore, bolts screwing into metric nuts cast in the slab were used to connect the slab and girder. The nuts were welded onto the reinforcement bar in the slab before pouring. If all bolts are engaged in the nuts and tightened, the structure condition corresponds to the undamaged state. The damage of shear connectors is introduced into the structure by unscrewing several specific metric bolts to simulate the failure of shear links.
Four relative displacement sensors were fabricated and mounted on the bridge model. Figure 2 shows a developed relative displacement sensor prototype installed on the bridge. One end of the sensor is fixed on the steel girder with two screws, and the other end concrete slab. This installation is much easier than the vision-based approaches to measure the relative displacement, which need to setup a number of cameras or other optical devices. The inaccessibility of the interface between slab and girders makes the setup of cameras and laser displacement sensors difficult. This also explains the motivation to develop such sensor to directly track the behavior of shear slip for the purpose of structural health monitoring of composite bridges. A National Instruments (NI) data acquisition system was setup and used for data recording and quick in-situ analysis.

Figure 2. Developed relative displacement sensor prototype

Figure 3. Experimental setup for moving load tests

Figure 3 shows the experimental setup to carry out the dynamic test of the composite bridge under a moving load. A simple vehicle model was fabricated in the lab by using a steel beam with two concrete blocks on top to simulate the mass. A roller system was designed and the crane was used to pull the vehicle to travel on the top of the bridge model with a constant speed as the pulling force of the crane is steady and stable. A fabricated track was placed on the top of the concrete slab to make sure the vehicle is easy to move on a predetermined travelling path. The travelling speed of the vehicle is about 0.066m/s. Four accelerometers, four relative displacement sensors and three laser displacement sensors were mounted on the bridge model to measure the responses for damage detection. The performance by using different quantities of measured responses for damage detection of shear connectors under the moving load is investigated. Basically, the accelerometers are located at about the same locations as the relative displacement sensors. The relative displacement sensors are defined as S1, S2, S3 and S4, and accelerometers A1, A2, A3 and A4, respectively. The laser displacement sensors are placed at one-quarter, center and three-quarter of the span to measure the deformation of bridge, and they are numbered as D1, D2 and D3, respectively. The locations of all the sensors are shown in Figure 4. The shear connectors connecting the slab and girder are denoted as SC1 to SC32. The relative displacement sensors and accelerometers are placed in the center of two shear connectors, for example, S1 and A1 are placed in the center of SC1 and SC2. It should be noted that S1 and S4 are located close to the support locations.

Figure 4. Sensor placement configuration
Results and Discussions

In this study, both CWT and HHT will be employed to investigate and compare the performance of using different response quantities, such as relative displacement, acceleration and displacement, for the damage identification of shear connectors in a composite bridge subjected to a moving load.

Dynamic moving load test was conducted with shear connector SC3 removed. The sampling rate is set as 2000Hz. Only the measured data from the damaged state were used for the damage detection. The responses from S1, A1 and D1 are analyzed, and CWT and HHT are performed to identify the condition of shear connectors. Figures 5(a), (c) and (e) show the measured time-histories and CWT contours of relative displacement (S1), acceleration (A1) and displacement (D1), respectively. By comparing these three figures, the identification with displacement in Figure 5(e) is the worst one to detect the damage and fails to locate the damage, indicating the displacement is least sensitive to the change of structural conditions. Figure 5(c) shows that CWT of acceleration measurement is able to detect the true damage location with a bright area around 2.6-2.7m. However, there is a false identification at location about 1m from the right support, probably due to the surface conditions of the track that caused the vehicle model to impact the bridge model. Acceleration normally has a good performance for the damage identification. However, at the same time, the accelerometer is also sensitive to responses induced owing to changing surface profile and the surrounding environment conditions. Therefore using acceleration response for identification may give false identification as evidenced by the first peak in Figure 5(c). The measured relative displacement response and its CWT are shown in Figure 5(a). A bright area is observed at the true damage location in higher scales of wavelet transform diagram, which indicates that the introduced damage can be identified by using the relative displacement clearly with no false identification.

EMD is employed to extract the IMFs from the measured relative displacement, acceleration and displacement responses, respectively. HHT is performed and the spectra are calculated from the extracted IMFs. Figures 5(b), (d) and (f) show the calculated Hilbert spectrum from measured responses of S1, A1 and D1, respectively. The relative displacement clearly identifies the location of the introduced damage as shown in Figure 5(b). The acceleration response also detects the damage location correctly, however, gives some false identifications at 0.8m, 1.0m and 1.6m, which again may be caused by the disturbances due to the surface conditions as discussed above. The displacement fails to provide any useful damage indication information, which also means that the displacement has the worst performance to identify the damage of shear connectors. Analyses on the displacement responses measured by the other two laser displacement sensors, which are not shown here, also show the same results, i.e., displacement responses are not able to track the damage information on shear connector. This proves again that the deformation measurement is least sensitive to the shear link damage among the three response quantities. Analyses of the relative displacements measured by sensors S2, S3, S4 also failed to detect the damage, indicating they are not in the sensitivity radius of the sensor (about 0.5–0.9m) as discussed in a previous study (Li et al. 2013a). Accelerometers A2, A3 and A4 have the similar behavior as A1 and two spikes are observed, indicating the acceleration responses are sensitive to damage in shear connectors and changes in other conditions. Therefore they are prone to false identifications. These figures are not shown in this paper for the concise presentation purpose.

Both CWT and HHT from relative displacement and acceleration responses can accurately detect the damage of shear connectors. HHT gives more sensitive damage feature with a sharp contrast in the spectrum than CWT for the purpose of structural health monitoring. By comparing the performance of damage detections with acceleration and relative displacement respectively, the relative displacement gives better damage indication information without false identifications. Acceleration response also leads to successful damage identification, but is prone to give false identifications because it is very sensitive to changes, including the change in loading conditions from moving vehicle owing to varying bridge road surface conditions.
This paper presents the capability of using the relative displacement measurements to identify the damage of shear connectors in composite bridges under operational conditions with time-frequency analysis methods. Experimental studies are conducted on a slab-on-girder composite bridge model. CWT and HHT are employed to identify the damage of shear connectors in composite bridges with the relative displacement, acceleration and displacement. Damage detection is conducted when the bridge is subjected to a moving vehicle. It is demonstrated that both relative displacement and acceleration responses are good candidates for damage detection of shear connectors in composite bridges. HHT gives more sensitive damage feature with a sharp contrast in the spectrum than CWT for the purpose of structural health monitoring. By comparing the performance of damage detections with acceleration and relative displacement respectively, the relative displacement gives better damage indication information without false identifications.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from Australia Cooperative Research Centre for Infrastructure and Engineering Asset Management (CIEAM-II) "Supporting Infrastructure Management by Combining Sensors and Asset Information Models - Project No. 3104", and Australian Research Council Discovery Early Career Researcher Award DE140101741 “Development of a Self-powered Wireless Sensor Network from Renewable Energy for Integrated Structural Health Monitoring and Diagnosis”.

ACMSM23 2014

1177
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