DAMAGE DETECTION OF GUSSET PLATE CONDTION IN TRUSS BRIDGES BASED ON WAVELET PACKET ENERGY PERCENTAGE

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ABSTRACT

This paper investigates the possibility and effectiveness of using a recently developed relative displacement sensor for the damage detection of gusset plate conditions in steel truss bridges. The developed sensor is an innovative design offering some advantages and unique features, and is a much easier and cheaper method of structural health monitoring due to the simplicity of its direct measurement of relative displacement without the need for a stable reference point. To investigate the potential applications of the developed sensor to the damage detection of joint conditions, a steel truss bridge model is fabricated in the laboratory and installed with the developed sensors to detect the loosen bolt damage in the gusset plates by using measured relative displacements. Those measured relative displacement measurements from the free vibration tests of both the undamaged and damaged truss models are analyzed, and a damage index based on the wavelet packet energy percentage change is used to detect the existence of the loosen bolt damage in steel truss bridges. Experimental studies demonstrate that the developed relative displacement sensor has a sensitive performance to indicate the joint conditions in steel truss bridges.

KEYWORDS

Damage detection, steel truss bridge, gusset plate, loosen bolt damage, wavelet packet energy percentage, relative displacement sensor.

INTRODUCTION

Steel truss bridge is a main engineering structure type, which plays an important role in the transportation network. It is considered as an economical and reliable long span bridge solution. In such bridges, the joint connection conditions are essentially significant to guarantee the rigidity and load-carrying capacity of bridges. The overstress or distortion in the joint connection would result in the condition degradation and damage accumulation, which might eventually cause a catastrophic failure of the bridge if not carefully inspected or detected. The collapse of the I-35W Bridge in Minnesota is a recent disaster that exposes the weaknesses in current visual inspection practices and structural health monitoring of steel structures (Gastineau *et al*. 2009). I-35W was a highway bridge over the Mississippi river that collapsed on August 1, 2007. The national transportation safety board identified the gusset plate U10W was the likely point of the initial failure (Liao and Okazaki 2009). The collapse of this bridge draws attention to steel structures failing under the strain of ageing and the increasing loading demands placed upon them. Holt and Hartman (2008) suggested that the strength of the gusset plate was insufficient to develop the shear forces expected at this panel point. Investigations into the failure showed that the gusset plates were giving warning signs in the form of out-of-plane displacements in the months leading up to the disaster. Ocel and Wright (2008) investigated and found out that those out-of-plane displacements in the gusset were a contributing factor to the collapse and caused the direction of movement that matched the physical evidence. The fact that these warning signs went undetected indicates that a more sophisticated structural condition monitoring strategy is required.

In this paper, a newly developed relative displacement sensor, which is used to directly measure the relative displacement between two points, is briefly reviewed. To investigate the potential applications of this sensor to structural joint condition monitoring, an experimental steel truss bridge model is fabricated and installed with the developed sensors to measure relative displacements at joint connections. Experimental studies with free vibration testing measurements are conducted to demonstrate if the relative displacement sensor is capable of identifying the minor changes in the bolt connection of joints in truss bridges. Wavelet packet decomposition is performed with the measured responses. A damage index based on the change in the energy percentage of some specifically selected wavelet packet component energy to the total wavelet packet energy is calculated to identify the damage in the gusset plate of steel truss bridges.

METHODOLOGY

Relative Displacement Sensor

A relative displacement sensor, which is able to measure relative displacements between two points based on the principles of the Wheatstone bridge circuit, has been developed and its accuracy has been validated. This sensor is developed to be an efficient and cost-effective approach to measure relative displacement whilst offering its own unique advantages. It is very sensitive to the relative movement between two points on the structure, and is also easy to be directly mounted on the structure without the need for a stable reference point. The investigations on the sensor's accuracy and ability in monitoring the relative displacements due to the shear connection damage of composite bridges have been conducted (Li *et al.* 2015). Comparing with traditional measurements from laser displacement sensors and accelerometers, experimental studies demonstrated the advantages of using this new sensor, which offers an innovative tool to be utilized in a structural health monitoring system, to detect the shear connection conditions for composite bridges under moving load excitations (Li and Hao (2015)). Taking the advantages of the decent performance of the developed relative displacement sensor in detecting the shear displacement, this paper will study if this sensor could be successfully applied for monitoring other structural systems, in particular the joint conditions in steel truss bridges.

The sensitive component of the sensor is a square metallic block around 20mm with two ends installed on the testing structure. The square metal block in the center is as thin as 1mm to prevent the installed sensor affecting the structural local stiffness. Four strain gauges are placed on the square metal component as four diagonal members to construct a Wheatstone bridge circuit. The four arms of the Wheatstone bridge circuit are formed by the resistors R_1 to R_4. The output voltage of the full bridge is calculated based on the principle of Wheatstone bridge circuit (Wheatstone 1843) as follows

$$\frac{v}{U}=\frac{1}{4}(\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}+\frac{\Delta R_3}{R_3}-\frac{\Delta R_4}{R_4}) \tag{1}$$

where v and U are output and input voltages, respectively. ΔR_1, ΔR_2, ΔR_3 and ΔR_4 are the resistance variations of the four resistors R_1 to R_4, respectively.

The relationship between the input and output voltages is

$$v=\frac{1}{4}\cdot k\cdot U\cdot(\varepsilon_1-\varepsilon_2+\varepsilon_3-\varepsilon_4) \tag{2}$$

where $\varepsilon_1, \varepsilon_2, \varepsilon_3$ and ε_4 are strains of the four resistors R_1, R_2, R_3 and R_4, respectively. k is the gauge factor, which is about 2 for metal strain gauges. Equation (2) indicates that the base values those four resistors are not important as long as the gauge factors are equal.

A relative displacement d along the horizontal direction of the sensor, will deform the four strain gauges differentially due to the diagonal orientation, so that the relative displacement appears as shear distortion of the sensor. With four strain gauges deformed in diagonal orientations, we have the following relationship

$$\varepsilon=\varepsilon_1=-\varepsilon_2=\varepsilon_3=-\varepsilon_4 \tag{3}$$

Substituting Equation (3) into Equation (2), the output voltage due to the shear distortion is

$$v=\frac{1}{4}\cdot k\cdot U\cdot(\varepsilon_1-\varepsilon_2+\varepsilon_3-\varepsilon_4)=k\cdot U\cdot\varepsilon \tag{4}$$

From Equation (4), the output voltage is linearly proportional to the strain ε and hence d for a given input voltage with a constant strain gauge factor. The supplying input voltage for the developed sensor is 2.5V. A calibration test is necessary to find out the constant K in the following equation between measured strain and relative displacement

$$d=K\cdot\varepsilon \tag{5}$$

The sensor may actually suffer not only shear distortion, but also tension, compression, bending and torsion effects in real applications. In order to highlight the signal-to-noise ratio of the relative displacement measurements, it is desirable to minimize the sensor output due to tension, compression, bending and torsion effects. This is achieved by taking advantages of the symmetry of the used Wheatstone bridge circuit. More details about the sensor's design idea and features can be referred (Li et al. 2015).

Damage Index Based on Wavelet Packet Energy Percentage Change

Damage detection is conducted based on the change in the wavelet packet energy percentage, which is the change in the energy of the selected wavelet packet components with respect to the total energy of all the wavelet packet components. The damage index has been defined as follows (Li *et al*. 2014)

$$DI = \frac{|P_d - P_{ud}|}{P_{ud}} \tag{6}$$

where DI is the damage index, P_d and P_{ud} are the percentages of selected wavelet packet components energy to the total energy of all the wavelet components under the damaged and undamaged states, respectively. It should be noted that this is a non-model based damage detection since the finite element model of the structure is not required and only the vibration measurements are processed for the wavelet packet decomposition and damage index calculation. However, it should be noticed that this damage index requires the measurement information from the baseline structure for the comparison of structural vibration properties and the identification of structural condition change.

EXPERIMENTAL INVESTIGATIONS

Experimental studies on a steel truss bridge model in the laboratory are conducted to investigate the possibility and effectiveness of using the developed relative displacement sensor for the damage detection of gusset plate conditions in truss bridges. A steel truss model is constructed with four 50mm×50mm×5mm equal angles for the beams and 50mm×5mm flat bars for the chord members as shown in Figure 1. M6 bolts are used to connect all the chord members and gusset plates to the equal angles. More than 300 bolts are used in the whole bridge model. The truss model has a length of 2m, width 0.35m and height 0.5m. The truss bridge model is placed on two steel frames which are fixed to the ground. A static loading is applied on the bridge model by using a hydraulic loading frame.

Three relative displacement sensors are installed on a joint connection in the central bottom of the truss to monitor the relative displacements that could occur under different loadings and damage scenarios. One end of the sensor is fixed on the gusset plate and the other end on the chord member so that the relative displacement between the gusset plate and the chord member surfaces will be detected and measured. A National Instruments dynamic data acquisition system was used for data recording. The setup of those relative displacement sensors provides an easy installation than vision-based approaches, which need to setup a number of cameras or other optical devices. The laser displacement sensors or cameras also require a fixed reference point for the setup, and may not be able to target the interface between the gusset plate and chord members to measure the relative displacement. This is a highlighted superiority of the developed relative displacement sensor, which enables the direct installation on the bridge for uniquely measuring the relative displacement for structural health monitoring purposes.

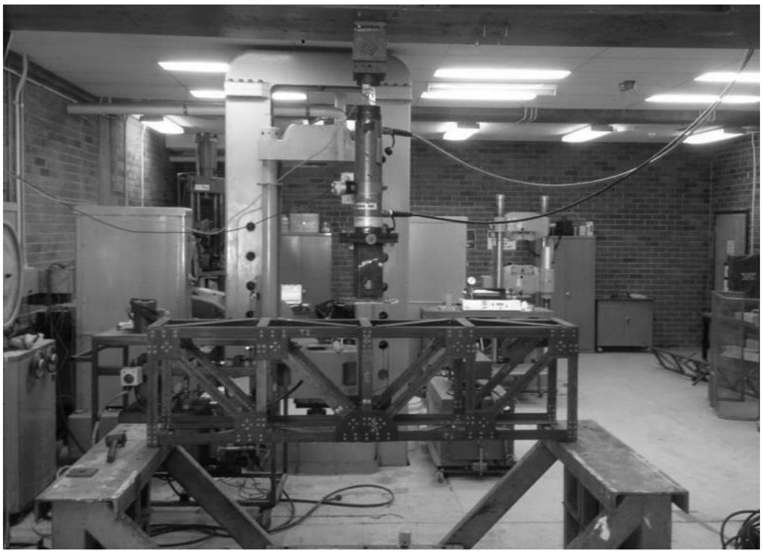

Figure 1 Steel truss bridge model in the laboratory

Figure 2 shows the sensor locations on the truss bridge model. Sensors 1 and 3 are orientated diagonally so as to detect both the vertical and horizontal relative displacements while sensor 2 will only detect the horizontal relative displacement. Damage can be introduced by loosening the specific bolts in different joint connections. The sensor will output a time-history strain, which can be converted to a time domain relative displacement record using a calibrated sensitivity. The aim is to investigate the feasibility of using the relative displacement in detecting structural local bolt damage in the joints of truss bridges. If all bolts are engaged in the nuts and tightened, the structure condition corresponds to the undamaged state. It may be noted that the bolt is fully unscrewed to simulate the local damage in the joint condition. It is interesting to note the detection with partial damage in a single bolt is not covered in this study because of no available equipment in the laboratory to introduce partial damage to an individual bolt. However, in this study, only a single bolt is removed in a single joint connection to introduce the partial damage in the joint connection of truss bridges.

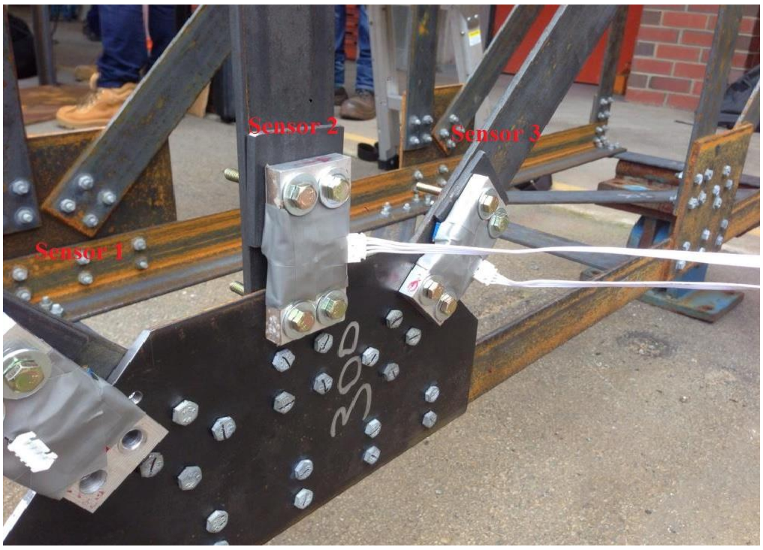

Figure 2 Sensor setup on the target gusset plate

The face of the truss bridge model installed with the sensors is defined as the front face. Figure 3 shows the numbering of joints in the front face of the truss bridge model and the exact bolt removed separately at different joints to simulate the different damage scenarios. For example, for the damage scenario on Joint 1, only the marked bolt on Joint 1 as shown in Figure 3 is removed. Other joints are still in the intact conditions. Damage detection is conducted with the vibrational relative displacement measurements from structural free vibration tests under the intact and damaged states. The rapid release of the static load results in the free vibration of the truss structure. Relative displacements are measured separately from the free vibration tests under both the intact and damaged structural states. Four damage scenarios are considered in this study, i.e. a single damaged bolt in Joint 1, Joint 2, Joint 5 and Joint 6, respectively. The damage index as shown in Equation (6) is computed based on wavelet packet decomposition analysis of measured relative displacement responses. Two measurements from the undamaged model are analysed to obtain the baseline information of the proposed damage index.

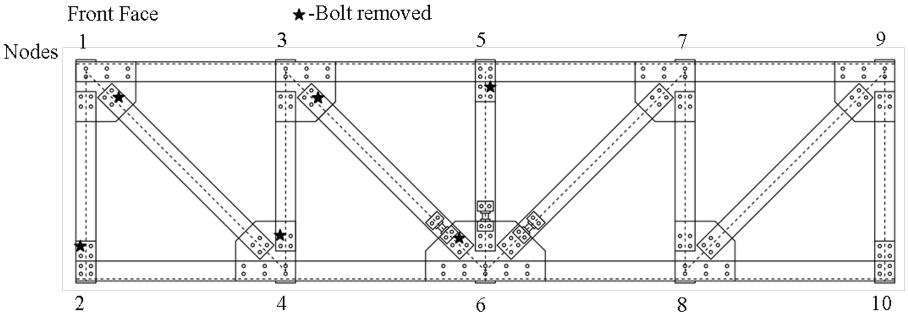

Figure 3 The numbering of joints in the front face of the model and the removed bolt at different joints

The fundamental natural frequency of the intact structure is identified as 8.44Hz by performing a FFT analysis for the measured relative displacement at Sensor 1 under free vibration, as shown in Figure 4. Table 1 shows the identified fundamental frequencies from the undamaged and damaged states with a damaged bolt in Joints 2 and 6. The modal analysis from the measured responses from the damaged structure shows that the identified first frequency is 8.22Hz as shown in Figure 5 with a local bolt removed at Joint 6. Another damage scenario is that the damage occurs at the support node, i.e. Node 2. The identified frequency is 8.24Hz as shown in Figure 6. The frequency reductions are less than 3%, which is very small. This will make the damage detection with frequency change information difficult and subject to environmental and noise effect. A band pass Infinite Impulse Response (IIR) filter with Chebyshev Type II filter and passband frequency from 1 to 20 Hz is defined to pre-process the measured relative displacements and remove the high frequency noise effect. Those filtered responses are then used for the wavelet packet decomposition and computation of damage index. It is noticed that a level 7 wavelet packet decomposition is performed and the second packet with the frequency range from 7.8Hz - 15.6Hz which covers the fundamental mode is used to calculate the damage index in Equation (6).

Table 1 Identified fundamental frequencies from undamaged and damaged states

Undamaged	Damaged State (Joint 2)		Damaged State (Joint 6)	
Frequency	Frequency	Change	Frequency	Change
8.44 Hz	8.24 Hz	2.4%	8.22 Hz	2.6%

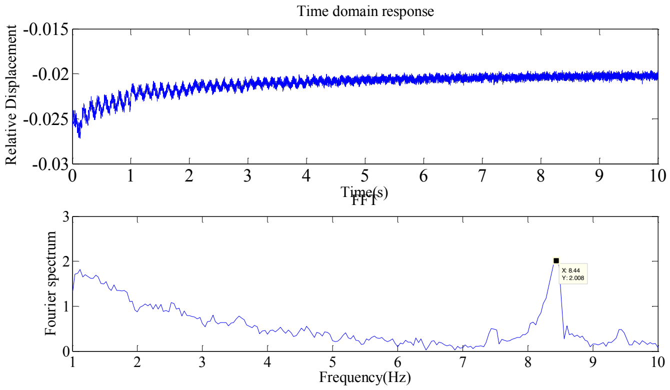

Figure 4 Measured relative displacement from Sensor 1 under free vibration of undamaged structure

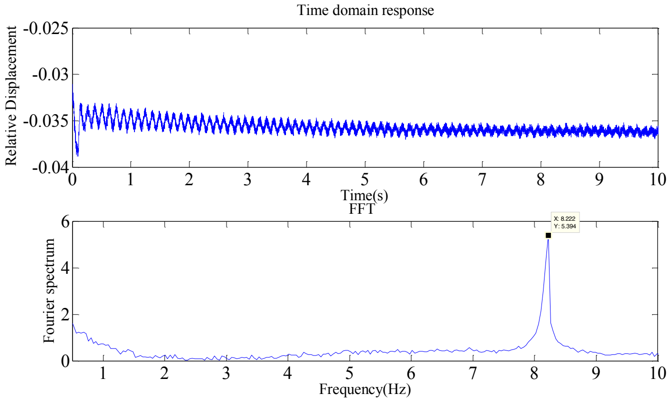

Figure 5 Measured relative displacement from Sensor 1 under free vibration of damaged Joint 6

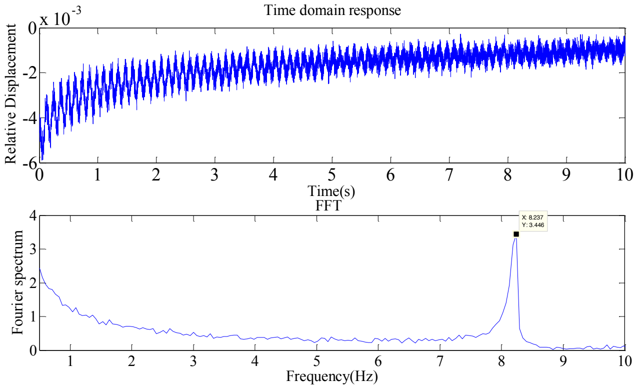

Figure 6 Measured relative displacement from Sensor 1 under free vibration of damaged Joint 6

Only the measured responses from Sensor 1 and Sensor 2 are used in this study as Sensor 3 is targeting the right side of the truss bridge model from Joint 7 to Joint 10. Figure 7 shows the damage detection results with the energy percentage of the above selected wavelet packet to the total wavelet packet energy. It can be observed that the calculated damage index values from Sensors 1 and 2 at different damage scenarios are higher than the baseline values, which demonstrates that the used damage index based on wavelet packet energy percentage is effective to detect the loosen bolt damage in the joint connections of the steel truss bridge. However, Sensor 1 generally has a better performance than Sensor 2 since significantly higher damage index values are observed from Sensor 1. The explanation is that Sensor 1 can detect the relative displacements not only in the horizontal but also the vertical directions because it is installed on the diagonal chord member while Sensor 2 only measures the horizontal relative displacements. It is also seen from Figure 7 that the calculated damage index values from both sensors are higher for the damage scenarios with the loosen bolt introduced in Joints 5 and 6, which are close to the installed sensors. This is expected because the relative displacement sensors are better to detect the local damage in the nearby area. It is also worth noting that Sensor 1 is capable of identifying the damage in the support location, i.e. Joint 2. The damage detection results from free vibration tests demonstrate that the used damage index is very sensitive and effective in various damage scenarios, and the sensor installed on the diagonal chord member connected to the gusset plate has a better performance to detect the local damage effect.

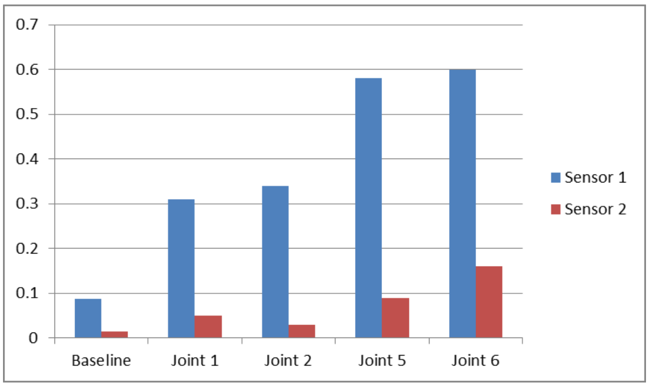

Figure 7 - Damage detection results with wavelet packet energy percentage

CONCLUSIONS

This paper investigates the effectiveness of using a recently developed relative displacement sensor for the damage detection of gusset plate condition in steel truss bridges. The damage detection is conducted by analysing the relative displacement measurements under free vibration tests from both the undamaged and damaged truss bridge models. The energy percentage of specific wavelet packet components to the total wavelet packet energy is used to calculate the damage index and identify the bolt loose damage in the joint connections of steel truss bridges. A steel truss bridge model is fabricated and installed with the developed sensors to detect relative displacements in the central bottom of the gusset plate. Experimental studies are conducted to validate the proposed approach. The relative displacement measurements from free vibration tests are conducted to investigate if the sensor measurements can be used to identify the existing damage in structures by comparing the calculated damage index from various damage scenarios to the baseline index. The results demonstrate the feasibility and effectiveness of using the relative displacement sensor as an effective tool in structural health monitoring to assess the gusset plate condition and structural integrity of truss bridges.

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