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Health monitoring of joint conditions in steel truss bridges with relative displacement sensors

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ABSTRACT

This paper investigates the feasibility and effectiveness of using a recently developed relative displacement sensor for the structural health monitoring of joint conditions in steel truss bridges. The developed relative displacement sensor is an innovative design offering some advantages and unique features, and is a much easier and economical method for structural health monitoring due to the simplicity of its direct measurement of relative displacement without the requirement for a stable reference point. To investigate the performance of applying the developed relative displacement sensors for structural joint condition monitoring, a steel truss bridge model is fabricated in the laboratory and installed with the relative displacement sensors to detect the health conditions of joint connections. The dynamic relative displacement measurements are analyzed with a time-frequency analysis method, i.e. continuous wavelet transform, which is a well-practiced signal processing technique to identify the structural condition change, namely the loosen bolt damage in the joint connection of steel truss bridges under ambient vibrations. The sensitivity range of the developed sensor is also investigated to see how sensitive the sensor is to identify the local bolt damage. Relative displacement measurements of the steel truss bridge models under free vibration tests from both undamaged and damaged states are also analyzed, and a damage index based on the change in the percentages of a specific wavelet packet component to the total wavelet packet energy between the undamaged and damaged states 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 identify and assess the joint conditions in steel truss bridges.

1. Introduction

Structural health monitoring aims to give a non-destructive evaluation of the structural condition state at any given moment of its intended life time [6]. It is important for engineers to be able to assess the structural integrity to ensure its safe operations. A major consideration of a structural health monitoring system is the ability for the system to distinguish what is the structural 'normal' or 'healthy' behavior, over a long term evaluation period to prevent a 'failure' condition [3]. An ideal structural health monitoring system would detect and locate damage at an early stage. Infrastructure in the civil and transportation industry is ageing at a rapid pace that is accelerated by the increased volumes and demands of modern traffic, which places more strain on the services than originally designed. It is important to improve the current methods and tools available to work toward an ideal system, new developments will enhance structure functionality, increase relia-

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bility and safety, lower maintenance costs and improve the structural service life.

Steel truss bridge is a very typical form and vital part of civil infrastructure worldwide. It is considered as an economical and reliable long span bridge solution. 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 [6]. 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 [11]. 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 Hartmann [10] 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 [16] 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 sophisticated structural condition monitoring strategy is required. The current ongoing monitoring and maintenance practices of these structures are dependent on visual inspections and nondestructive tests. Improving the information and tools available for owners/operators will greatly assist in the effectiveness of a continual health monitoring and economic asset management.

After the collapse of the I-35W bridge, evaluating and monitoring the gusset plate connections has been a focus of transportation agencies. Finite element analysis has been conducted to investigate the critical gusset plate in the I-35W bridge [8,12]. Gusset connection evaluations and analyses based on finite element analysis need accurate geometric data of the gusset plate and fastener locations. A large scale of uncertainties may also exist in the bridge structure, i.e., in the stiffness, mass, geometry and boundary conditions, which will make the finite element analysis difficult to accurately identify the joint conditions. Berman et al. [2] recently proposed a rapid assessment approach termed as triage evaluation procedure (TEP) to identify overstressed gusset plate. The proposed approach in the TEP is to check if the maximum Whitmore stress of all members intersecting the gusset plate satisfies the criteria. Federal Highway Administration [5] issued a technical advisory to provide guidance to bridge owners as to which nondestructive evaluation technologies can be used to supplement gusset plate inspections when visual techniques are not feasible. The technical advisory recommended the use of ultrasonic testing to determine the section conditions in gusset plates. Ultrasonic relies on imparting high-frequency elastic stress waves into a material and using sensors to measure the response. Reflections of the stress waves from the structural damage, i.e., cracks, corrosion, etc. appear as peaks in the frequency spectrum. The main limitation of ultrasonic testing is that the stress wave attenuates in the gap between multiple layers of plates [17]. It should be noted that both the visual and ultrasonic inspections need access for inspectors to the target area and a significant amount of labor input and time. Current visual inspection techniques are expensive, time consuming, and require expertise knowledge, while new and improved nondestructive techniques are vital in improving the health condition monitoring of gusset plates in truss bridges. A radiographic testing approach has been developed to identify the pattern of section loss in gusset plates [17]. Higgins and Turan [9] recently developed digital imaging tools for evaluation of gusset plate connections in steel truss bridges. The geometric dimensions of the gusset plate and fasters were measured by processing the taken images.

This paper briefly reviews a newly developed relative displacement sensor, which is used to directly measure the relative displacement between two points. The developed sensor is very sensitive to the relative movement between two points on the structure, and is also easy to be directly mounted on the structure. It does not require a stable reference point therefore it is easy to be setup and is cost-effective to measure the relative displacement. The feasibility and sensitivity of the developed relative displacement sensor for the joint condition monitoring of steel truss bridges are studied in this paper. To investigate the performance of applying the developed relative displacement 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. The dynamic relative displacement measurements are analyzed for online monitoring by using a time frequency analysis method, i.e. continuous wavelet transform (CWT), which is a well-practiced signal processing technique to identify a change in structural condition under ambient vibrations. The sensitivity range of the developed sensor is also investigated to see how sensitive the sensor is to identify the local bolt damage under ambient vibrations.

Experimental studies with free vibration testing measurements are also conducted to demonstrate if the relative displacement sensor is capable of identifying the minor changes in the joint connection conditions in steel truss bridges. Wavelet packet decomposition is performed with the measured relative displacements from both the undamaged and damaged structural states. A damage index based on the change in the percentages of a specific wavelet packet component energy to the total wavelet packet energy between the undamaged and damaged states is calculated to identify the loosen bolt damage in the joint conditions of steel truss bridges.

2. Developed relative displacement sensor

A new relative displacement sensor, which is able to detect relative displacements between two points utilizing 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 while offering its own