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Fatigue cracking detection in steel bridge girders through a self-powered sensing concept

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ABSTRACT

Development of fatigue cracking is affecting the structural performance of many of welded steel bridges in the United States. One of the main sources of fatigue cracking is out-of-plane distortion occurring at connections of transverse structural members and longitudinal girders. Distortion-induced fatigue cracks mostly occur in older bridges with members prone to fatigue. Prediction of secondary stresses in these members is difficult using conventional design specifications. This limitation suggests the necessity of utilizing new strategies to analyze the damage caused by distortion-related cracking. This study presents a new approach for detection of distortion-induced fatigue cracking of steel bridges based on the interpretation of the data provided by a newly developed self-powered piezo-floating-gate (PFG) sensor. The PFG sensors are empowered using piezoelectric transducers through harvesting energy from the mechanical loading experienced by the structure. In order to assess the performance of the proposed sensing system, three-dimensional finite element models were developed and the structural response of the girder was subsequently obtained. The fatigue life of the girder was determined based on J-integral concept and Paris Law. Several damage states were defined by extending the fatigue crack lengths. Thereafter, features representing the PFG sensor output were extracted from the strain data for different sensing nodes to detect the damage scenarios. Furthermore, a new data fusion concept based on the effect of group of sensors was proposed to improve the damage detection performance. The results indicate that the proposed method is capable of detecting different damage progression states. This is specifically evident for the sensors that are located close to the damage location. The acceptable performance of the proposed sensing system implies its applicability for other modalities of infrastructure/structural health monitoring (I/SHM).

1. Introduction

A major concern in maintenance and preservation of steel bridges is cracking of structural members. Fatigue cracking is one of the most important phenomena affecting the structural integrity and performance of welded steel bridges [1–3]. Occurrence of fatigue cracks is specifically of great importance for the steel bridges built before the 1970s. This is because the fatigue design specifications were not appropriately defined until 1970s and 1980s [4]. In general, fatigue cracks can occur in welded steel bridges due to low fatigue resistance structural members, members with large initial defects, members subjected to out-of-plane distortion, and details at end restraints and flange terminations [5]. However, out-of-plane distortion is known as the major source of fatigue cracks leading to severe structural deficiency. Distortion-induced fatigue is more about the detailing issue and needs much fewer stress cycles to develop compared to other crack types.[3] Different factors can cause out-of-plane distortion such as impact of vehicles on an expansion joint not perpendicular to the traffic flow, thermal forces on skewed and horizontally curved bridges, differential deflection of the adjacent beams, etc. [6]. The mechanism of fatigue crack formation is schematically shown in Fig. 1. A feature of the diaphragms and cross frames is primarily to distribute loads among main elements (Fig. 1a). These elements are fastened to transverse stiffeners welded to the girder web. For many of the bridges designed before 1989 AASHTO Standard Specifications [7], no connection was considered between the stiffeners and the steel girder flanges. Consequently, out-of-plane fatigue cracks are developing at small web gaps at the girder flanges, webs, and stiffener plate connections due to out-of-plane bending of the girder web [1]. Accordingly, stress state increases in the web near the weld and fatigue cracks initiate in the heat-affected zone of the weld near its toe. Such distortion-induced fatigue cracks may occur as horizontal or horseshoe cracks at the top or bottom of girder diaphragm connections (Fig. 1c). The cracks usually propagate away from the weld. The direction of the crack propagation changes as the crack grows in length [8,9].

Several retrofitting methods have been proposed to deal with this type of damage [8,9]. However, selection of an appropriate repair strategy is complicated and depends on many factors. On the other hand, there are no major predictive models to assess the damage caused by distortion-related cracking [9]. Distortion-induced fatigue cracking is a

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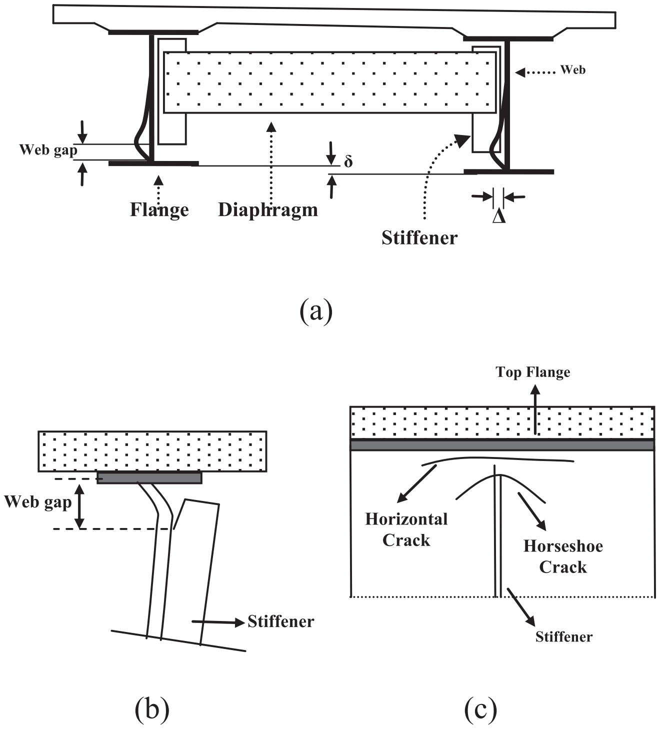

Fig. 1. Distortion-induced fatigue cracking: (a) web distortion due to differential displacement between two girders; (b) out-of-plane distortion; (c) fatigue cracks.

progressive phenomenon. Thus, from an infrastructure/structural health monitoring (I/SHM) perspective, it is crucial to detect the damage progression at early stages so that severe damage to the bridge structure can be prevented. Recently, significant research has been conducted on utilization of new sensing technologies for damage identification in steel structures [10–26]. In this context, it is well-understood that deploying and maintaining of traditional wired sensors is a difficult task. More, managing huge amount of data generated by a dense array of wired sensors is very challenging and costly [27]. To cope with these limitations, wireless sensor networks (WSNs) are increasingly utilized as alternatives to traditional structural engineering monitoring systems. The significant capability of WSNs for sensing the physical state of the structural systems has attracted considerable attention in recent years [27–32]. WSNs are not merely monitoring systems but also autonomous data acquisition nodes [29,30]. Dense arrays of low-cost smart wireless sensors can offer useful data about the structural deterioration. Such information can be efficiently used to enhance the performance of the SHM systems [27]. However, a major concern for the application of wireless sensors is about their power supply. Harvesting ambient energy seems to be an attractive solution for tackling this issue [33]. Energy harvesting is the possibility of converting mechanical energy into electrical energy [34]. Among various self-powering energy sources, piezoelectric transducers are proved to be one of the most efficient choices [35–38]. For SHM, piezoelectric transducers can be used for the self-powering of wireless sensors by harvesting energy from the mechanical loading experienced by the structure [39].

In this context, a new class of self-powered wireless sensors (SWS) has been recently developed and deployed by the authors [39–42]. This sensor uses piezoelectric transducers to empower an array of ultra-low power floating gate computational circuits. SWS has a series of memory cells that cumulatively store the duration of strain when the amplitude of the input signal, coming from the piezoelectric material, exceeds different thresholds. The recorded cumulative durations are stored on-board the sensor since it is installed and can be periodically read using a Radio Frequency Identification (RFID) scanner [39]. One of the main advantages of this sensing system is the fact that it is "response-based". All the effects due to variations in load location, load magnitude, traffic wander, environmental effects such as temperature

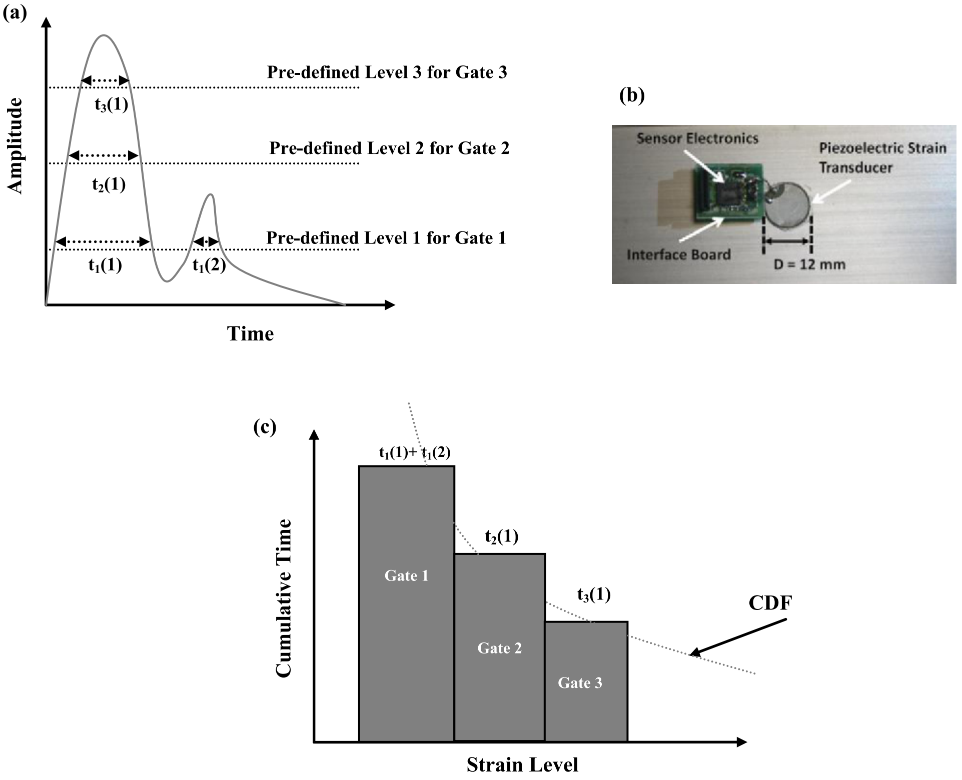

Fig. 2. The prototype and working principle of the self-powered PFG sensor.