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Structural health monitoring of steel frames using a network of self-powered strain and acceleration sensors: A numerical study

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ABSTRACT

This study presents a novel approach to detect damage in steel frames using a hybrid network of piezoelectric strain and acceleration sensors. A numerical study has been conducted on a steel frame with bolted connections to verify the accuracy of the proposed method. The damage is introduced to the frame structure by loosening the bolts and creating cracks on its structural members. The frame is subjected to cyclic loading. Circular Lead Zirconate Titanate (PZT) piezoelectric transducers and bimorph PZT cantilever plates are used as strain and acceleration sensors, respectively. The strain and acceleration time histories are obtained from the finite element (FE) model. A theoretical model is used to obtain the voltage output delivered by the PZTs. Initial damage indicator features are defined by fitting a Gaussian mixture model (GMM) to the sensors output histograms. Moreover, a new sensor fusion model is proposed to improve the accuracy of the damage detection approach. The numerical results indicate that strain-based sensors and accelerometers are, respectively, more sensitive to cracks and bolt loosening. The hybrid system of sensors is efficient in detecting and localizing both types of damages in steel frames.

1. Introduction

Structural health monitoring (SHM) systems have been extensively implemented to monitor the performance of civil infrastructures [1,2]. A variety of SHM techniques have been developed to detect damages in different types of steel structures [3–7]. Technical literature was reviewed concerning the SHM in civil infrastructures using techniques and devices that monitor changes in structural response [3,5,6]. Using self-powered wireless sensors (SWS), an intelligent approach was developed to detect structural damages, e.g., cracking of steel gusset plate joints [4], and distortion-induced fatigue cracking of steel bridge girders [7]. Arguably, two of the most common damage types in bolted steel frames are loosening of bolt joints and cracking [8]. The stiffness of connections is of significance to steel frames since it critically affects the dynamic response and integrity of structures. Many studies have been conducted to analyze the impacts of bolts loosening on the mechanical response of steel frames. Yang et al. [9] presented a reduced-order numerical model for damage detection on loosening of frame connection bolts. An adaptive quadratic sum-square error with unknown inputs (AQSSE-UI) algorithm was proposed to address experimental data and obtain damage assessment of steel frame joints [9]. Based on the changes of structure's natural frequencies, Zhu and He [10] developed an approach to identify damages, e.g., loosening of bolted connections, in space frame structures with L-shaped beams. Shao et al. [11] developed a bolt looseness detection technique based on the frequency shifting of piezoelectric impedance. This technique allowed precise design and control over axial preloads on bolts. Lei et al. [12] examined the effects of joint damages in frame structures under earthquake excitations. The authors proposed an algorithm based on a two-step Kalman filter approach to detect damages of bolt joints under seismic loads. Dohler and Hille [13] presented a model to predict structural damages of steel frames by detecting changes of model parameters and comparing with a reference state. Abdeljaber et al. [14] developed a structural damage detection system using one-dimensional convolutional neural networks. An inherent adaptive design was presented to fuse feature extraction and classification blocks into single and compact learning body. Yin et al. [15] numerically studied connection loosening of frame structures using vibration-based damage detection. Noisy incomplete model data were addressed in Bayesian framework based on model reduction technique. Many studies have also been conducted on cracking of welded beam-column connections in steel structures. Alemdar et al. [16] developed a repair method to

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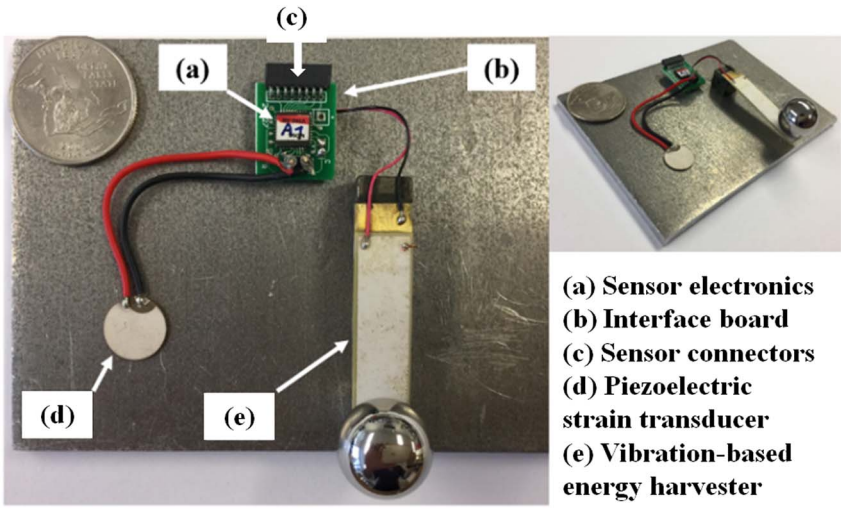

Fig. 1. Prototype of the self-powered sensing system.

retrofit the cracks of steel frames caused by distortion-induced fatigue. Hu et al. [17] carried out an experimental study on welded cracking of high strength steel frames under seismic excitations. Nearly all of the previous studies are focused on analyzing one type of damage in steel frames. This implies the necessity for developing a new approach that accurately detects the combined impacts of cracks and bolts loosening in steel frames.

Wireless sensor networks (WSNs) play a key role in SHM of steel frames and other structures and hence, studies have been conducted to improve the performance of WSNs [18–21]. Deployment of WSNs was studied to reliably diagnose structural response while reducing energy consumption [18]. A wireless, real-time pressure monitoring sensor was developed [19]. Various WSNs mechanisms were proposed for SHM with respect to different structures and applications, e.g., a cyber-physical co-design approach for beam and truss structures [20], or WSNs based on strain and acceleration sensors to assess earthquake damages [21]. Hu and Wang [22] investigated the application of WSNs for SHM in highway steel bridges. The authors presented a customized WSN platform that flexibly combined a variety of sensors, namely accelerometers, strain gauges, temperature sensors, with relatively low power consumptions. Bhuiyan et al. [23] proposed a solution to deploy wireless sensors at strategic locations to obtain the best structural detection data. More literature review of SHM using wireless sensor networks can be found in Lynch and Loh [1]. However, nearly all the commercially viable sensors require an external power source. As a result, the limited lifespan of batteries becomes a major challenge for wide applications of WSNs. A comprehensive review regarding this issue was carried out by Akhtar and Rehmani [24].

In order to overcome the power limitation, the authors have developed a new class of SWS for different applications [25–28]. Vibration in civil infrastructures was deployed as a source of ambient energy to power the SWS [27]. The Self-powered piezo-floating-gate (PFG) sensors were then used for: 1) smart pavement monitoring systems [26] to detect different damages such as bottom-up cracking in asphalt concrete pavements [28], and 2) WSNs with non-constant injection rates for SHM of steel structures [25]. The sensor is powered by the energy harvested by a piezoelectric transducer. Attaching the SWS to civil infrastructures, localized strain statistics can be measured to detect potential damages at early stages [4,7]. Previous research funded by the Federal Highway Administration (FHWA) revealed the capabilities of the SWS in detecting crack propagation in steel and pavement structures. In fact, the performance of this sensing system has been evaluated merely in detecting local damage (i.e., cracks) in structures based on the strain response.

The main goal of this study is to establish a local-global damage detection approach based on the sensing mechanism of SWS. The research objective is achieved by analyzing the data obtained from a hybrid network of strain and acceleration self-powered sensors. Piezoelectric strain transducers are used to detect the local damage on the frame (i.e., cracks), while bimorph piezoelectric cantilever beams are used to detect the change in the boundary conditions (loosening of bolts). The damage detection mechanism presented in this study can be divided into the following phases:

- Development of a 3D finite element (FE) model for a steel frame under different damage scenarios.
- Extraction of strain and acceleration data from the FE model subjected to cyclic loading.
- Estimation of the voltage output generated by the piezoelectric harvesters from the strain and acceleration signals.
- Generation of the sensor output histograms for each sensing node.
- Extraction of features from the sensor distribution in order to define preliminary damage indicators.
- Fusion of the strain and acceleration data to identify new features that have a sound relationship with the damage progression in the structure.

2. Self-powered wireless sensor

The sensing unit consists of two main components: a piezoelectric transducer and a floating-gate sensor. The prototype of the SWS is shown in Fig. 1. This new class of wireless sensors is designed to monitor structural response. The piezoelectric strain transducer (Fig. 1(d)) and accelerometer (Fig. 1(e)) generate electricity by harvesting the mechanical energy from the host structure. Many techniques and mechanisms have been presented to increase the efficiency of this energy conversion process [29–32].

A series of memory cells are placed adjacent to the computational circuits to record the duration of voltage events when the amplitude of the input signal, coming from the piezoelectric material, exceeds different thresholds. The output of the sensor is presented in the form of a histogram, in which each bin denotes the cumulative time of events at a predetermined load level. Fig. 2 illustrates the procedure of obtaining the histogram generated by the SWS. Fig. 2(a) presents the voltage generated by the piezoelectric transducer under an external excitation. Fig. 2(b) shows the amount of charge on the sensor gates after electron injection. The cumulative voltage of each memory gate j can be estimated as,

$$V_j^s = V_0 - I_j \times \sum_{i=1:7} \Delta t_i^j \tag{1}$$

where V_j^s is the voltage on the sensor (volts) at gate j, Δt_i^j is the duration

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