Construction and Building Materials 144 (2017) 728–746

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# A self-powered surface sensing approach for detection of bottom-up cracking in asphalt concrete pavements: Theoretical/numerical modeling

Hassene Hasni, Amir H. Alavi *, Karim Chatti, Nizar Lajnef

*Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA*

## HIGHLIGHTS

- A self-powered surface sensing approach for detection of bottom-up cracking in asphalt concrete (AC) pavements.
- Interpretation of compressed data stored in memory cells of a self-powered sensor with non-constant injection rates.
- A realistic dynamic moving load was applied to the surface of the pavement.
- Definition of several damage states using Element Weakening Method.
- Gaussian mixture and computational intelligence approaches for multi-class damage classification.

## ARTICLE INFO

*Article history:*
Received 14 September 2016
Received in revised form 19 March 2017
Accepted 26 March 2017

*Keywords:*
Pavement health monitoring
Self-powered wireless sensor
Finite element modeling
Moving load
Data fusion
Damage detection
Computational intelligence

## ABSTRACT

This study presents a surface sensing approach for detection of bottom-up cracking in asphalt concrete (AC) pavements. The proposed method was based on the interpretation of compressed data stored in memory cells of a self-powered wireless sensor (SWS) with non-constant injection rates. Different 3D finite element (FE) models of an AC pavement were developed using ABAQUS to generate the sensor output data. A realistic dynamic moving load was applied to the surface of the pavement via DLOAD subroutines developed by FORTRAN. A network of sensing nodes was placed at the top of the AC layer to assess their sensitivity to the progression of bottom-up cracks. Several damage states were defined using Element Weakening Method (EWM). A linear-viscoelastic behavior was considered for the AC layer. In order to detect the damage progression, several damage indicator features were extracted from the data acquisition nodes. The damage detection accuracy was improved through a data fusion model that included the effect of group of sensors. The proposed fusion model was based on the integration of a Gaussian mixture model (GMM) for defining descriptive features, different feature selection algorithms, and a robust computational intelligence approach for multi-class damage classification. Furthermore, an uncertainty analysis was carried out to verify the reliability of the proposed damage detection approach. The results indicate that the progression of the bottom-up cracks can be accurately detected using the developed intelligent self-powered surface sensing system.

## 1. Introduction

Structures health monitoring (SHM) is focused on detection of damage in structures at early stages using advanced technologies. Pavement health monitoring is an extension of the SHM concept that deals with assessing the structural state of pavement infrastructure systems. Distresses concentrated in asphalt concrete (AC) layer can lead to the failure of the pavement structure over time. The maximum tensile stresses are commonly developed at the bottom of the AC layer under repetitive loadings. As a result, cracks usually initiate at the bottom of the asphalt layer and start propagating to the surface of the pavement. This so-called bottom-up fatigue cracking is one of the main failure modes in asphalt pavements. The fatigue life of pavements is mainly related to the nature and the amplitude of the applied loading. A dynamic analysis and a realistic loading modeling are essential to provide accurate prediction of the pavement response. However, most of traditional pavement analysis methods assume a uniform circular loading area and a stationary analysis. Previous studies show that

---

* Corresponding author.
*E-mail addresses:* ah_alavi@hotmail.com, alavi@msu.edu (A.H. Alavi).

http://dx.doi.org/10.1016/j.conbuildmat.2017.03.197
0950-0618/

these assumptions may result in an unrealistic pavement response [1,2]. Dynamic loading may increase the fatigue damage by a factor between 2 and 7 [1]. Under the dynamic wheel effect, rutting damage may reduce the service life of the pavement by at least 40% [2].

Furthermore, Yoo and Al-Qadi [2] showed that the dynamic pavement response is usually higher than a quasi-static analysis. In fact, the pavement dynamic response is essentially a function of the structure natural frequency as well as the external loading frequency. Yoo and Al-Qadi [2] concluded that there is about 39% difference on the tensile strain at the bottom of the asphalt layer between a static and transient dynamic analysis. Gillespie et al. [3] argued that a truck speed of 36 mph has a loading frequency of about 4.6 Hz, and 6.5 Hz for 51 mph. Lourens [4] reported that the magnitude of the stress and deflections in pavement highly depends on the loading frequency and they are different from the results given by a static loading. Since 1940s, flexible pavements are usually modeled as a linear elastic multilayer system based on the theory of the two-layered elastic systems developed by Burmister in 1943. However, hot-mix asphalt (HMA) behaves as a viscoelastic material. This type of material exhibits time-, rate- and temperature-dependent behavior. Al-Qadi et al. [5] and Elseifi et al. [6] showed that the approximation of multilayered linear elastic system underestimates the pavement responses at high temperatures or under a slow moving load. Furthermore, the HMA mixture behaves as an elastic material only at low temperatures and high loading frequencies. Therefore, an efficient pavement modeling should consider both the variation of the loading in time and space, the material on frequency and temperature and the amplitude of the applied stress.

From a sensing perspective, strain gages are widely used in roadways to detect variations in strains associated with pavement deterioration [7–10]. However, the installation of many of the existing sensors demands considerable care during construction. The commonly-used H-shaped strain gages require precise individual placement and wiring systems. To cope with these limitations, recent development in the field of pavement health monitoring has revealed the capabilities of wireless sensors networks (WSN) [11–18]. However, nearly all of the available wireless sensors need an external power supply to activate the sensor. As a consequence, periodic replacement of the sensor battery is needed. This becomes more challenging and sometimes impractical for the long-term pavement health monitoring. Therefore, energy harvesting methods have been used for the empowering of the sensors [15,19]. One of the most efficient energy harvesting methods is the use of piezoelectric transducers. This family of material has the ability of converting the mechanical energy into an electrical charge by harvesting the micro-strain energy from structure. Thereafter, by embedding a network of the piezoelectric transducers inside the asphalt pavement layer, they can generate electricity needed to empower the sensor. In this context, a self-powered wireless sensor (SWS) has been developed at Michigan State University (MSU) based on the “smart” pebble concept [10,20,21]. There are very few studies on the applicability of this sensor for SHM [10,15]. In the pavement health monitoring area, Lajnef et al. [10] showed that the pavement fatigue life can be predicted using the SWS. Alavi et al. [14] have tested the ability of the sensor in detecting and localizing bottom-up cracks in asphalt pavement using the SWS with constant injection rate. They embedded the sensor inside the AC layer using a spherical epoxy packaging. The sensing system was placed two inches far from the bottom of the layer. Finite element (FE) simulations were performed to assess the strain amplitude changes due to bottom-up cracking [14]. The developed FE models were based on an elastic material behavior and a quasi-static loading. Moreover, Alavi et al. [14] showed that only the sensors located above the crack experience a notable change due to damage growth. However, a disadvantage of embedding the sensors at the bottom of the AC layer is that they may be damaged due to excessive stresses. Furthermore, new pavement construction projects are negligible when compared to the extent of the exiting pavement network. It is thus more critical for State Highway Agencies (SHAs) to adopt monitoring techniques that can be adapted to existing pavements. It should be noted that surface sensing technologies such as remote sensing are commonly used for the monitoring of existing pavements. These methods use the electromagnetic spectrum to identify the surface and subsurface defects. In this context, ground-penetrating radar (GPR) employs the electromagnetic energy to detect subsurface anomalies. GPR can be used for both measuring the pavement thickness and locating voids. GPRs are able to identify cracks and measure cracks depth between 50 and 160 mm in flexible pavements. They can be attached to a service vehicle travelling at highway speed [22]. However, major limitations of such methods are that they need notable energy to operate and may not be practical for continuous long-term monitoring purposes.

In order to cope with the limitations of the existing monitoring methods, this study proposes a self-powered wireless surface sensing approach for the detection of bottom-up cracking in existing asphalt pavements. The proposed method would not have major interference with regular pavement maintenance activities. The SWSs can have floating-gates with constant injection and non-constant injection rates. The previous research conducted by our team has been focused on the SWS with constant injection rate [14–18]. While the working principal is the same, the difference between the two classes of sensors is in the form of data outputted from the sensors. Herein, the non-constant injection rate sensor was used. A dynamic analysis of a moving truck at highway speed was carried out through a realistic FE modeling. Different damage scenarios were considered by changing the size of the damage zone and the AC material properties. The sensor output was modeled based on the strains extracted from the surface of the AC layer at different sensing nodes. The sensors locations were defined in the longitudinal and transversal directions. Thereafter, features were extracted from the sensor data and fused to define new set of explanatory features. Finally, a probabilistic neural network (PNN) classifier was used to classify the predefined damage scenarios.

## 2. Finite element modeling of pavement structure subjected to a moving load

### 2.1. Geometry and FE model

ABAQUS software was employed to simulate the response of the pavement under a moving load. In the FE analysis, the stress/strain response is sensitive to the element type and size as well as the boundary conditions. In this study, 3D FE models were developed as they are more appropriate compared to a 2D axisymmetric model. In fact, a 3D model allows simulating the contact stresses between the tire footprint and the pavement surface. The pavement model was meshed using two different types of elements: eight-node linear brick elements with reduced integration (C3D8R) and eight node linear infinite elements (CIN3D8). The standard finite elements were used to model the region of interest and the infinite elements were deployed in the far field region. This type of elements allows providing silent boundaries to the FE model in the dynamic analysis and reduces the number of elements at far field [23]. These elements have a special shape function to vanish the displacement field when the coordinates approach infinity. Such boundary type can minimize the reflection of the shear and dilatational waves back into the FE mesh [24,25]. In a dynamic analysis, the infinite elements introduce additional