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Influence of asphalt on fatigue crack monitoring in steel bridge decks using guided waves

Lotfollah Pahlavan[a,*], Mariana M. Mota[b], Gerrit Blacquière[c]

[a] Department of Structural Reliability, TNO, Van Mourik Broekmanweg 6, 2628 XE Delft, The Netherlands
[b] Department of Process and Instrumentation Development, TNO, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands
[c] Department of Acoustics and Sonar, TNO, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands

HIGHLIGHTS

- The role of asphalt in guided-wave propagation in steel deck plates is disclosed.
- The temperature-dependent behavior of asphalt is incorporated in the analysis.
- A good correlation between the numerical and experimental results is demonstrated.
- The effect of asphalt on the accuracy of a crack sizing methodology is quantified.
- The extent of the effect of asphalt in the system depends on its type/composition.

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ABSTRACT

Asphalt materials generally exhibit temperature-dependent properties, which can influence the performance of fatigue crack inspection and monitoring systems for bridge deck structures. For a non-intrusive fatigue crack sizing methodology applied to steel decks using ultrasonic guided waves, the effect of asphalt has been investigated. A higher-order spectral finite element model has been implemented to capture the propagation characteristics of guided waves in the multi-layer waveguide. Experimental evaluation has been performed on an aluminum plate covered with bitumen. The results reveal that the extent of the effect of asphalt on propagation of guided waves depends on the type and layout of the asphalt. For a particular asphalt type of interest, i.e. open asphalt surfacing, however, this effect appeared to have limited influence on the performance of the crack sizing methodology, i.e. in the order of a few percents. In the analysis, temperature variation, and uncertainties in the material properties and asphalt bonding condition have been taken into account.

1. Introduction

The structure of orthotropic steel bridge decks is commonly composed of a deck plate with an asphalt layer on the top, and longitudinal stiffeners and transverse crossbeams welded to the bottom side. Being subject to dynamic traffic loads often higher than the anticipated design load, fatigue cracks grow under such welded intersections, which have become a major challenge in asset management of steel bridges [1–6]. Such cracks may not be visually inspectable until they completely propagate through the deck plate and the asphalt layer, see Fig. 1. When this situation occurs, the integrity of the structure may already be at risk. Identification of these cracks at an earlier stage is therefore desirable. Furthermore, if combined with load monitoring and crack growth models [6,7], such early stage identification can have substantial added value in predictive maintenance of the structure.

The currently applied inspection techniques for identification of such cracks are (i) predominantly associated with a large detection limit due to the measurement through the asphalt, e.g. pulsed eddy current (PEC), or due to a detection dead-zone, e.g. phased array (PA), or (ii) require asphalt removal associated with high cost and traffic hindrance, e.g. time-of-flight diffraction (TOFD). A non-intrusive baseline-free sizing methodology utilizing ultrasonic guided waves was proposed by Pahlavan and Blacquière [8]. They showed that the guided-wave signals with zero-angle incidence collected at one side of the weld line under inspection can be used to compute the crack profile at the intersection of orthogonal stiffeners. The methodology was demonstrated for sizing of real fatigue

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* Corresponding author.
E-mail addresses: pooria.l.pahlavan@tno.nl (L. Pahlavan), mariana.mota@tno.nl (M.M. Mota), gerrit.blacquiere@tno.nl (G. Blacquière).

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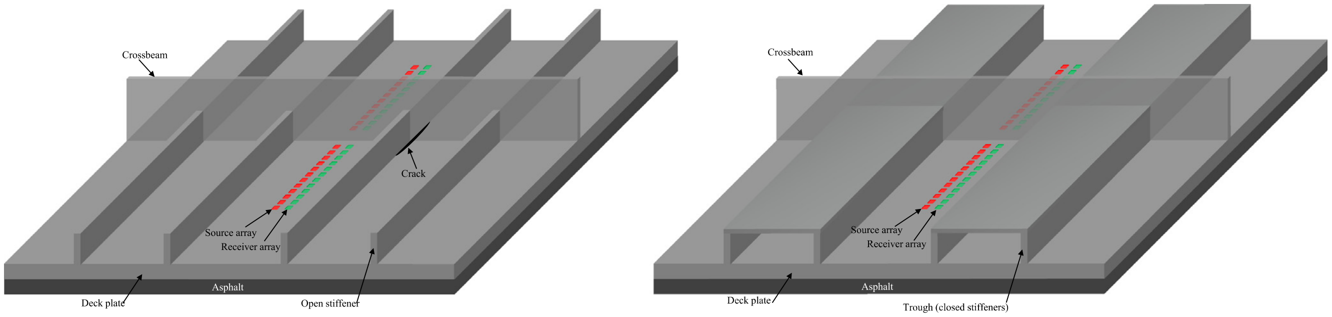

Fig. 1. Schematic structure of steel bridge decks. The longitudinal closed stiffeners may have a trapezoidal cross-section. For guided-wave crack sizing [8], source and receiver transducer arrays are mounted on the deck plate. The pictures are shown upside-down for better illustration. The crack becomes non-visible when the longitudinal stiffeners are so-called closed.

cracks in a mock-up bare bridge deck under dynamic loading. However, application of this technique in the field yet requires an investigation on the influence of asphalt on propagation of guided waves and possible mitigation. One possible challenge is that the coupling of the main waveguide with asphalt and the increased damping may distort the signals and lead to reduced accuracy for the inspection system. This topic is elaborately addressed in the present paper.

Asphalt is generally a heterogeneous viscoelastic material which exhibits a strong temperature-dependent behavior [9–12]. In order to study the influence of asphalt on the guided-wave crack sizing methodology, the homogenized temperature-dependent model of the asphalt presented and experimentally evaluated by Larcher et al. [9] is adopted in this paper. Based on the plane-wave excitation of guided waves in the crack sizing methodology [8], a 2D higher-order spectral finite element method (SEM) of the multi-layer deck plate-asphalt layers is constructed. This method captures the interaction of the guided waves in the deck plate with the asphalt overlay. Subsequent to an experimental validation of the model on an aluminum plate covered with bitumen, the paper further focuses on a so-called open asphalt surfacing, which includes four layers with different material properties. This type of asphalt applies to a number of important highway bridges in The Netherlands. Through various case studies, the influence of temperature variation, uncertainty in the asphalt properties, and possible asphalt debonding on the propagation of the diagnostic guided waves, i.e. fundamental symmetric mode (S0), is quantified. Furthermore, the effect of asphalt on the reflectivity of the stiffener and crack underneath is studied, from which the resulting uncertainty in the crack sizing is estimated.

The paper is organized as follows: the theory of guided-wave crack sizing at the intersection of orthogonal stiffeners and the deck plate is presented in Section 2. General asphalt properties and their influence on propagation of guided waves in a deck plate are discussed in Section 3. Section 4 is devoted the numerical analysis using SEM. Section 5 deals with the experimental evaluation of the numerical model. A number of case studies on open asphalt surfacing are discussed in Section 6, which concludes with an error bound estimation for the crack sizing in the presence of asphalt.

2. Guided-wave crack sizing in steel deck plates

Baseline-free identification of fatigue cracks under orthogonal stiffeners-to-deck plate welds using ultrasonic guided waves has been elaborately discussed in Pahlavan and Blacquière [8]. For the sake of completeness and clarification of the context, the methodology is briefly outlined in this section. As shown in Fig. 1 (in an up-side-down view for better illustration), the method utilizes two arrays of ultrasonic transducers on one side of the (longitudinal) stiffener under investigation. They act as source and receiver arrays for transmission and reception of guided waves, respectively. Both arrays are placed between and parallel to the stiffener including the hot-spot and the one adjacent to it. The receiver arrays may be interrupted with a crossbeam. The wavefield is recorded using the receiver array. The distance of the arrays from the stiffener under investigation is designed such that the reflections from the opposite stiffener can be windowed out the in the time domain. Fatigue cracks with a negligible width dimension can grow under the weld line between the deck plate and the stiffener, parallel to the transducer arrays.

Monitoring of each hot-spot location requires a separate pair of transducer arrays optimized for S0 waves. When a transducer in the source array fires, the transmitted S0 waves are directly measured by the receiver array. After the interaction with the weld line with possible crack underneath, the incident waves experience scattering, diffraction, and mode conversion. Only a portion of the incoming S0 waves may remain as S0 due to mode conversion. The scattered part, i.e. the reflected wavefield, partly propagates back towards the receiver array. By means of wavefield extrapolation [13], the direct and the reflected S0 waves measured by the same receiver array are reconstructed at the stiffener location for extraction of the reflectivity information.

2.1. Field crack under longitudinal stiffener

The case with no crossbeam is discussed first. For a generally multi-model excitation/reception of guided waves, the wavefields recorded on the receiver array for the nth shot record can be expressed for an arbitrary frequency component as follows:

$$\vec{\mathbf{P}}^F_n(z_r,z_s,\omega)=\sum_i \mathbf{D}^i(z_r,\omega)\mathbf{W}^i(z_r,z_s,\omega)\vec{\mathbf{S}}^i_n(z_s,\omega), \tag{1}$$

$$\vec{\mathbf{P}}^R_n(z_r,z_s,\omega)=\sum_j\sum_i \mathbf{D}^j(z_r,\omega)\mathbf{W}^j(z_r,z_t,\omega)\mathbf{R}^{ji}(z_t,\omega)\mathbf{W}^i(z_t,z_s,\omega)\vec{\mathbf{S}}^i_n(z_s,\omega), \tag{2}$$

with,

$\vec{\mathbf{P}}^R_n$ the reflection response recorded at the receiver array,

$\vec{\mathbf{P}}^F_n$ the baseline response recorded at the receiver array,

$\mathbf{D}^i$ the detector matrix for mode-i each row of which representing the transfer function of a single detector for that mode,

$\mathbf{W}^i$ the propagation matrix of waves of mode-i,

$\vec{\mathbf{S}}^i_n$ the column vector representing the source wavefield of mode-i for the nth shot record,

$\mathbf{R}^{ji}$ the (mode $i \rightarrow$ mode j) reflection matrix at the stiffener z-location each column of which describing angle-dependent reflectivity at z_t,