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Fatigue crack sizing in steel bridge decks using ultrasonic guided waves

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ABSTRACT

A baseline-free quantitative sizing methodology utilizing ultrasonic guided waves for fatigue cracks under welded stiffeners in steel bridge decks has been developed. An inverse wavefield extrapolation-based formulation for obtaining the crack reflectivity and depth profile has been presented in the kernel of which, the presence of welded orthogonal stiffeners has been accounted for. Having conducted experiments on a test bridge deck subject to fatigue loading, it has been demonstrated that the crack profile can be estimated from the reflection coefficients obtained. In comparison with the reference measurements, the maximum crack depth estimation error turned out to be about 20%.

1. Introduction

Fatigue crack growth is one of the major fracture mechanisms of steel bridge decks [1–3]. The common structure of steel bridge decks is composed of a deck plate with an asphalt layer on the top, and (open or closed, i.e. trough) longitudinal stiffeners and transverse crossbeams welded to the bottom side. The most critical crack type, from structural as well as inspection point of view, often grows at the deck plate–trough–crossbeam intersection. Such cracks remain invisible until they completely propagate through the deck plate and the asphalt layer. The conventional inspection techniques for identification of such cracks predominantly (i) require asphalt removal associated with high cost and reduced traffic capacity, e.g. time-of-flight diffraction (TOFD), or (ii) have large detection limits exceeding a few centimeters either 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). Acoustic emission (AE) was utilized as an alternative for monitoring these fatigue cracks to alleviate the abovementioned issue [4–6]. Despite the demonstrated capability of crack localization, quantitative monitoring using existing AE technology is not yet feasible under realistic conditions. It is believed that a robust non-intrusive crack sizing technology (in both depth and length directions) can substantially assist the asset managers and the decision makers for proper actions regarding safety and minimization of the overhaul and repair costs due to such cracks.

Techniques based on ultrasonic guided waves are known to be effective for structural health monitoring (SHM). Such waves interrogate the structure for possible defects using temporarily or permanently installed transducers [7–11]. Guided-wave crack monitoring systems have extensively been applied in many different applications ranging from oil and gas to civil and aerospace sectors [12–15]. Among the existing techniques however, the ones offering quantitative sizing capability mainly deal with basic structures without notably complex geometrical features, e.g. welded stiffeners [16–18]. The geometrical complexity originates from the fact that such appendices to the structure disturb the wavefield, which in combination with the multi-modal and dispersive nature of the guided waves, can further complicate the interpretation of the acquired guided wave signals [19]. One common technique for monitoring complex structures using guided waves is to compare the response of the structure at the current state with that of the intact structure, i.e. its baseline response [20]. The baseline response, however, is not always known. Even if it is measured, it may vary over time due to mechanical and environmental loading of the structure [21–23]. It is believed that quantitative baseline-free methods for sizing of fatigue cracks in steel bridge decks, or other structures with similar level of complexity, have not sufficiently been addressed in the literature.

The present paper is a proof-of-concept for a sizing methodology for fatigue cracks at deck plate–trough–crossbeams intersections. The baseline response of the structure at the crack location is reconstructed merely from the information acquired from the current possibly damaged case. For single-mode excitation and reception of guided waves, the information collected at one side of the weld line under inspection is used to compute the reflection coefficients at the crack area. This approach is referred

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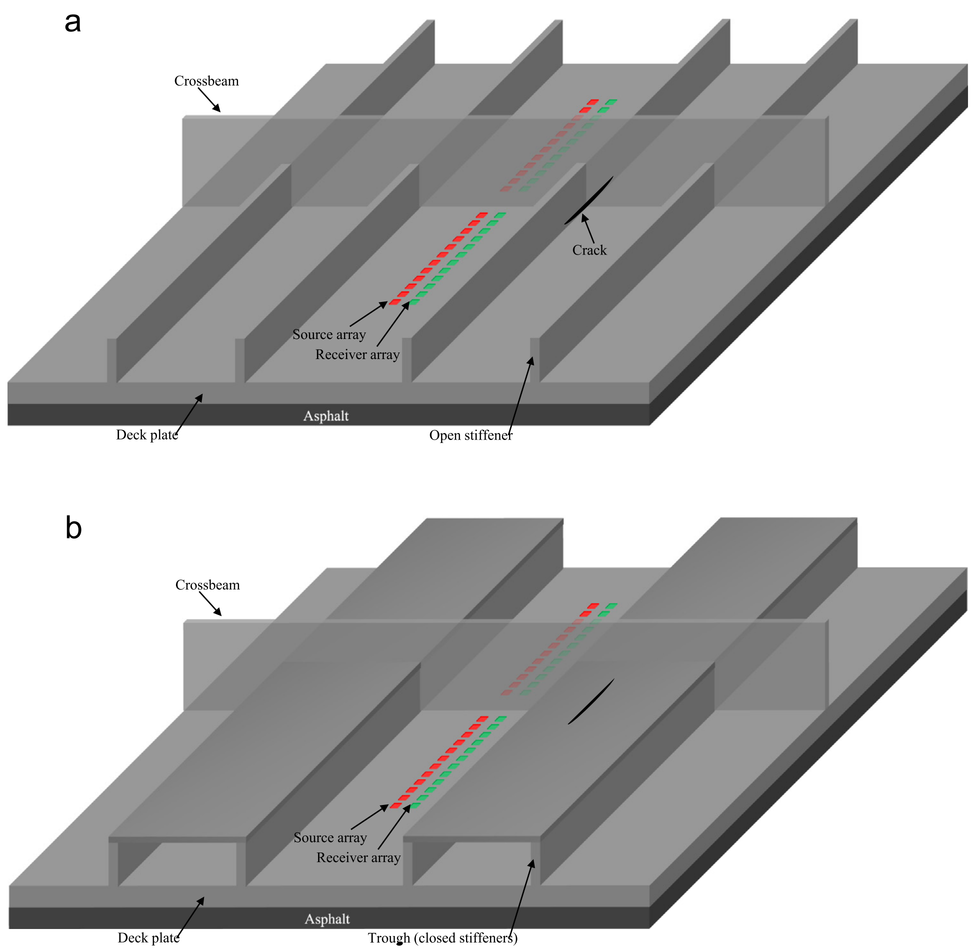

Fig. 1. The source and receiver arrays mounted on the deck plate. The pictures are shown upside-down for better illustration. The crack becomes non-visible when the longitudinal stiffeners are so-called closed.

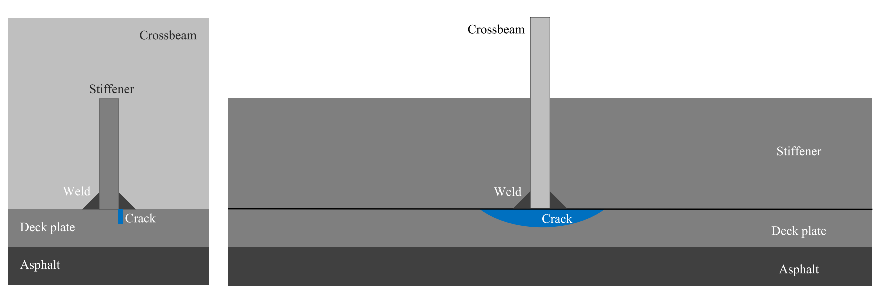

Fig. 2. Fatigue cracking at the intersection of the deck plate, crossbeam, and longitudinal stiffener.

to as the 'direct baseline measurement method' (DBM) in this paper. The wavefield recorded at the receiver array is reconstructed analytically at the weld line location using the wavefield extrapolation technique [24,25]. Once the reflection coefficients for the wave mode of interest are obtained, the crack depth is estimated using a characteristic curve obtained via a higher-order finite element method. Application of the proposed methodology has been demonstrated in the lab environment for sizing of real fatigue cracks in a mock-up bridge deck under dynamic loading.

Regarding the organization of the paper, extraction of the reflection and transmission operators in the direct baseline measurement method is discussed in Section 2. Influence of aperture limitation on the accuracy of the direct baseline measurement method is presented in Section 3. In Section 4, the presence of a crossbeam interrupting the transducer arrays is accounted for. Section 5 deals with the conversion of the reflection coefficients to crack depth. The experimental setup is described in Section 6. The results of the experiments are discussed in Section 7. The paper ends with a summary and concluding remarks.

2. The direct baseline measurement method

Two arrays of ultrasonic transducers on one side of the (longitudinal) stiffener under investigation are considered, which act as the 'source array' and the 'receiver array' for transmission and reception of guided waves, respectively. The layout of the transducers has been schematically shown in Fig. 1, in an up-side-down view for better illustration. Both arrays are placed between and parallel to the stiffeners including the hot-spot and the one adjacent to it. The receiver arrays may or may not be interrupted with a crossbeam. The wavefield is recorded using the receiver array.