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Interaction of ultrasonic waves with partially-closed cracks in concrete structures

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HIGHLIGHTS

- The interaction of ultrasonic waves with partially-closed cracks in concrete has been studied.
- The influence of crack opening and incident angle on the signal features has been evaluated.
- The width of the crack process zone has been estimated from the data.
- The anisotropy of the material at the crack zone has been quantified.

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ABSTRACT

Interaction of ultrasonic waves with partially-closed surface-breaking cracks in concrete structures has been studied. Measurements have been conducted on a reinforced concrete beam containing various mechanical-load-induced cracks and compared with the baseline measurements at those locations. Influence of crack width, incident angle of waves with cracks, and distance from the cracks on travel time and amplitude of the waves have been investigated when the beam was unloaded. It has been observed that a measurable part of the waves propagate through the cracks due to the acoustic coupling between the crack faces, although attenuation can be relatively high. The travel time has shown a nearly independent behavior from remaining crack opening in the measured range of 0.05 mm to 3 mm. Measurements in directions orthogonal and parallel to the crack suggest that there is substantial anisotropy in the cracking zone. Furthermore, an effective width of the micro-cracking area around the cracks has been estimated from the measurements.

1. Introduction

Surface-breaking cracks commonly occur in concrete structures. In reinforced concrete, development of such cracks can lead to increased risk and rate of corrosion by facilitating the transfer of corrosive substances to the reinforcement bars [4,7]. Proper identification and characterization of these cracks may therefore provide valuable input for improved assessment of structural reliability and durability of concrete structures.

Ultrasonic elastic-wave methods form an important class of non-destructive assessment techniques for concrete structures. Extensive investigations have been reported on characterizing the effect of cracks on ultrasonic waves in such media, see for example Liu et al. [9], Zerwer et al. [19], Shin et al. [17], Popovics et al. [14], Masserey and Mazza [10], Kee and Zhu [8], and Aggelis et al. [2]. Tomographic methods, as an example of a multi-dimensional assessment technique based on ultrasonic waves, have been implemented in various studies [5,16,1,18,3,15] in which the distribution of material stiffness is estimated from the distribution of speed of sound using an inversion scheme based on several pitch-catch measurements. Despite all the promising achievements, the majority of the reported methods are, in the kernel, either based on an idealized analogy of cracks to perfect notches, i.e. voids, or consider a simplified angle-independent transmission mechanism for ultrasonic waves through the cracks, due to which some inconsistencies in the reported observations can be identified. The acoustic coupling extent and details between the crack faces are expected to have a major effect on the diagnostic signals. For example, a perfect notch model is associated with strong scattering of the waves by the crack and diffraction from the crack tip, while a transmission model is associated with

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possibly-angle-dependent attenuation and time delay when the waves pass through the cracks. While there is general consensus that open cracks under substantial tensile stress can be described by the former model, closed and partially-closed cracks have been shown to allow a notable signal transmission [8]. For field application of elastic-wave-based assessment techniques and to minimize the contamination of the data with background noise, a particular situation of partially-closed cracks in the absence of excessive loads is of special interest (misalignment of aggregates may not allow perfect crack closure). The behavior of these cracks, to the extent that is desirable for application in a generic damage diagnosis method such as tomography, does not seem to have been sufficiently studied.

In this paper, a detailed investigation of the interaction of ultrasonic waves with imperfectly-closed cracks in an unloaded beam is presented. The designed experiments comprised five sets of measurements to quantitatively study: (i) the coupling variation of transducers, (ii) the baseline properties of the test sample, (iii) the influence of crack (remaining) opening on the signal features, i.e. amplitude and arrival time, (iv), the anisotropy in the crack zone, and (v) the effective width of the crack process zone. In each set, the responses have been compared to the baseline signal, i.e. the signal obtained when no defect was present. The results suggest that careful consideration of the crack behavior is essential in the development of passive and active elastic-wave-based techniques for assessment of existing concrete structures, such as acoustic emission and elastic-wave tomography.

2. Description of measurements

A brief theoretical background of the assessment approach is presented in this section. In order to study the effect of cracks on the diagnostic ultrasonic waves, a number of experiments have been designed and performed such that in each measurement set, a reference signal, i.e. baseline, is recorded alongside the signal influenced by the crack. For this, three transducers are used in each measurement, where one is transmitter and the other two are receivers, as schematically shown in Fig. 1. The receivers are placed at the same distance but opposite from the source.

When the transmitter coupled to the structure surface emits an ultrasonic pulse, it propagates inside the medium and on its surface. The recorded responses, i.e. the convolution of the source pulse transmitted into the concrete medium, the transfer function of the medium between the source and the receiver, and the transfer function of the receiver apparatus, at the two receiver locations (denoted by P_1 and P_2) can be described in the frequency domain as:

$$P_1(\omega) = \sum_i D_1^i(\omega) W^{ii}(l,\omega) S^i(\omega), \forall i \in [\mathrm{P},\ \mathrm{S},\ \mathrm{R},\ \mathrm{H}], \tag{1}$$

$$P_2(\omega) = \sum_j \sum_i D_2^i(\omega)[\bar{W}^{ji}(l,\omega) + \tilde{W}^{ji}(l,\omega)] S^i(\omega), \forall i,j \in [\mathrm{P},\ \mathrm{S},\ \mathrm{R},\ \mathrm{H}], \tag{2}$$

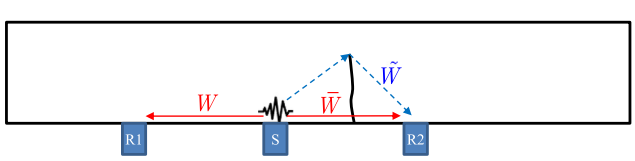

Fig. 1. Schematic illustration of the ultrasonic source (S) and receivers (R1 and R2) on the concrete member. In all the experiments, the transducers are placed such that a single crack under investigation is located between the source and one of the receivers.

where ω is the radial frequency, the superscript i and j denote the wave mode (each can denote pressure, shear, Rayleigh, and head waves), D_k^i is the transfer functions of receiver k for wave mode i, W^{ii} is the transfer function of the medium without crack for wave mode i, $\bar{W}^{ij}$ is the transfer function for waves entering the crack zone as mode i and leaving it as mode j, $\tilde{W}^{ij}$ is the transfer function for waves diffracted and possibly mode converted by the crack tip, l is the distance between the source and each receiver (similar in this case), and $S(\omega)$ denotes the generated pulse. The transfer function of the medium with crack may be simplified as:

$$\bar{W}^{ji}(l,\omega) = W^{ji}(l - l_c, \omega) Q^{ji}(l_c, \phi, \omega) \tag{3}$$

with Q the transfer function of the medium in the crack process zone affected by micro-cracking with effective length l_c. While W is a function of the base material properties and composition, Q (l_c,ϕ) can additionally depend on crack depth, transparency, and incident angle ϕ. These transfer functions may be obtained experimentally, analytically, or numerically.

For the comparison of the signals of the baseline and cracked cases to be meaningful, the coupling terms, i.e. D_1 and D_2, should be reasonably similar. The first set of the measurements in this research was hence dedicated to the quantification of coupling variation. The second set dealt with extraction of the properties of the medium (related to transfer function W) using an array of transducers. This information was necessary for estimation of the wave speed in the damaged area (related to transfer function Q) at a later stage. In the next measurement set, the influence of the crack opening on the signal amplitude and arrival time was studied (related to Q). Furthermore, the extent of the damage zone at the crack vicinity was assessed (related to l_c), followed by an assessment of the directional properties of the cracks (also related to Q).

3. Experiments

A reinforced concrete beam with length, height, and depth of 10 m, 0.8 m, and 0.3 m, respectively, which hosted several cracks of different opening and orientation, was chosen. The concrete class was C65 with compressive strength of about 68 MPa, and the maximum aggregate size was 16 mm. The cracks were generated in a shear test (not shown) under excessive loading, as schematically illustrated in Fig. 2. The beam was unloaded and placed on the floor of the laboratory, as can be seen in Fig. 3. A number of cracks with different remaining openings ranging from 0.05 m to 3 mm, which were measured with a crack width ruler on the beam surface, were selected for the ultrasonic tests. The data acquisition system was Sensor Highway II by MISTRAS, and the transducers where of resonant type with center frequencies of 60 kHz and 150 kHz, i.e. R6I and R15I, from the same vendor, used as both transmitter and receiver. The transducers were attached to the surface using a viscoelastic adhesive couplant.

3.1. Coupling sensitivity

Several measurement sets were performed to investigate the variation in the coupling of the transducers. To maintain the source signal constant at each set, four R6I transducers were placed on a circular pattern at a distance of 106.5 mm from the source, i.e. standard pencil lead break. This experiment was repeated 6 times at the same location on the beam by removing and re-installing the transducers.

3.2. Baseline properties

An array of 14 R6I transducers was mounted on the surface of the structure in an area without cracking. The spacing between