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Influence of the depth and morphology of real cracks on diffuse ultrasound in concrete: A simulation study

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ABSTRACT

The aim of the present paper is to simulate the propagation of diffuse ultrasonic energy in concrete in the presence of a real crack. The numerical model is presented and validated by the comparison with experimental data from the literature. Unlike most of the studies which consider a crack as a notch, a realistic crack morphology exhibits partial contacts along its lips. These contacts are modeled in order to study their influence on the diffusion parameters. The feasibility of determining the contact density of the crack is shown, revealing practice implications for non-destructive crack sizing and imaging in concrete.

1. Introduction

Cracking is critical for the structural integrity of civil engineering structures, as a consequence of the risks of mechanical failure and loss of impermeability which it can produce. In particular, the latter effect is induced by cracking of the concrete cover located between the surface and the first layer of rebar. This leads to the penetration of aggressive agents into the core of the structure, thus promoting corrosion of the rebar, leading to a degradation of the mechanical properties of the structure. The detection and characterization of such cracks is thus necessary, to allow the remaining lifetime of the structure to be predicted and its maintenance to be optimized.

Several difficulties are encountered in the use of acoustic techniques for the characterization of concrete in an industrial context. ISO and ASTM standards [1,2] state that ultrasound frequencies in the range between 20 kHz and 150 kHz should be used. The wavelength is thus greater than 3 cm, which does not allow real cracks to be detected efficiently before reaching the rebar located at few centimeter depth. When the frequency is increased, ultrasound measurements become more complex, in particular due to multiple scattering, resulting from the presence of aggregates similar in size to the ultrasound wavelength [3,4]. Various authors [5–7] have studied the ultrasonic characterization of cracks in concrete. They revealed a change in the waves' time of flight in the presence of a crack with controlled dimensions: a notch, whose walls have no contact points. Analogous results were observed with cracks produced by bending loads [8]. However, these cracks were opened artificially by applying a bending force to the test specimens, thus placing limitations on the accuracy with which they can represent real cracks.

A second approach [9], based on the analysis of diffuse ultrasound, was also studied for the purposes of concrete characterization. It shows that the complex propagation of multiple scattered waves in concrete can be simplified into a standard diffusion law. It is founded on the analysis of the ultrasonic energy diffusion by two parameters: the diffusivity D (with dimensions $[m]^2[s]^{-1}$), characteristic of the material's structure, and the dissipation σ (with dimensions $[s]^{-1}$), which reflects the medium's viscoelastic properties. Anugonda et al. [9] demonstrated the validity of this approach for concrete, both analytically and experimentally. They thus opened up numerous possibilities for the non-destructive characterization of microstructural damage in concrete. Becker et al. [10] thus studied the variation of diffusion parameters as a function of the aggregate diameters, whereas Punurai et al. [11] determined such variations in cement as a function of the quantity of occluded air. Deroo et al. [12] studied the influence of alkali silicate reaction on the diffusion parameters. Diffuse ultrasound was also analyzed in order to characterize cracks in concrete by Ramamoorthy et al. [13]. They showed that the diffusion parameters vary as a function of the length of a notch in concrete. Authors introduced another parameter: the arrival time of maximum energy (ATME). Quiviger et al. [14] confirmed the ability of ATME to characterize the opened portion of a real

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crack. According to the same authors, the ATME also varies as a function of the length of the closed portion of the crack. The presence of partial contacts along the length of the crack is assumed to be the cause of the observed variations.

The aim of the present study is to verify the influence of real crack morphology on the measured diffusion parameters. The morphology of a real crack in concrete and the numerical model are presented. This model is validated by the comparison with experimental data from concrete samples containing controlled notches. A real crack is then introduced by the study of the influence of partial contacts on diffuse ultrasound. Then, the numerical model is applied to the case of real cracks in concrete and compared to experimental data from the literature [14].

2. Crack morphology

The morphology of a crack, which is open at the concrete surface, has been described in [14]. The crack comprises two portions: the first is the open portion, located at the surface at the outer end of the crack. The second, in which the two walls are partially or totally in contact, is considered to be closed. The particularity of a real closed crack lies in the number and nature of the contact points or areas present between the walls. These modify the mechanical behavior of the crack, in particular as a result of local stress redistribution.

Turatsinze et al. [15] revealed a disparity in the profile of a crack produced by bending, similarly to the test specimens shown in Fig. 1(a) and (b) used in the present study. The crack exhibits a variable morphology, depending on its depth in the sample. These authors revealed the presence of discontinuities in the profile of the crack, lying in the median plane [Fig. 1(c) and (d)]. This is not a simple crack, but it can be represented in this zone by an interfacial crack with contact zones and interlocking effects.

Diffuse ultrasound in a concrete sample was numerically modeled by Ramamoorthy et al. [13] who studied the influence of a numerical notch on ATME. Seher et al. [16] numerically modeled diffusion in the presence of partially closed cracks. However, this study was performed using a commercial heat transfer software, thus the dissipation was taken into account by a post processing procedure (exponential decay). In the following, the numerical model including dissipation is presented and a realistic numerical crack is introduced.

3. Numerical simulation

3.1. The model

The computer code developed in the present study is based on a 2D finite difference method. This method is chosen mainly as a result of the simple geometry of the problem, the functional regularity of the energy, and the uniform diffusion which can be achieved inside the material. The results given by the numerical simulations are then compared with the experiments carried out by Quiviger et al. [14], with the decision to use a 2D model motivated by the symmetry of the test specimens used in the latter study, as well as by the resulting gain in computing time. The code is developed using Matlab®.

The concrete in which diffuse ultrasound propagates has fixed dissipation and diffusivity values. The size, the position of the sensors and the boundary conditions of the model are also fixed, to ensure that they match the experimental conditions. A rectangular mesh, with a horizontal resolution of 2 mm and a vertical resolution of 1 mm is used. It results from a compromise between maximum resolution along the axis of the crack, and lower resolution along the axis perpendicular to the crack, thus allowing the computing time to be optimized.

Diffuse energy is initiated by the experimentally determined energy spectrum of the 500 kHz sensor used in [14]. Ultrasonic energy diffusion is simulated by directly applying the general diffusion equation (Eq. (1)), using the energy emitted by the source (x_{exc}, y_{exc}), expressed in the form of a Dirichlet condition (Eq. (2)).

$$\frac{\partial}{\partial t}\langle E(x,y,t)\rangle + \sigma\langle E(x,y,t)\rangle = D\Delta\langle E(x,y,t)\rangle, \quad (1)$$

$$\langle E(x_{exc}, y_{exc}, t)\rangle = E_0(t), \quad (2)$$

Using $E_{i,j}{}^{(n)}$ to note the energy at point $(x_i, y_i)=(i\Delta x+x_0,\ j\Delta y+y_0)$, and at instant $n\Delta t$, the resolution scheme can be written in an explicit temporal form

$$\frac{E_{i,j}^{(n+1)}-E_{i,j}^{(n)}}{\Delta t} = -\sigma E_{i,j}^{(n)} + D\frac{E_{i-1,j}^{(n)}-2E_{i,j}^{(n)}+E_{i+1,j}^{(n)}}{\Delta x^2} + D\frac{E_{i,j-1}^{(n)}-2E_{i,j}^{(n)}+E_{i,j+1}^{(n)}}{\Delta y^2}, \quad (3)$$

This explicit form implies that the Courant-Friedrich-Lévy (CFL) condition is respected, i.e. that the temporal interval remains

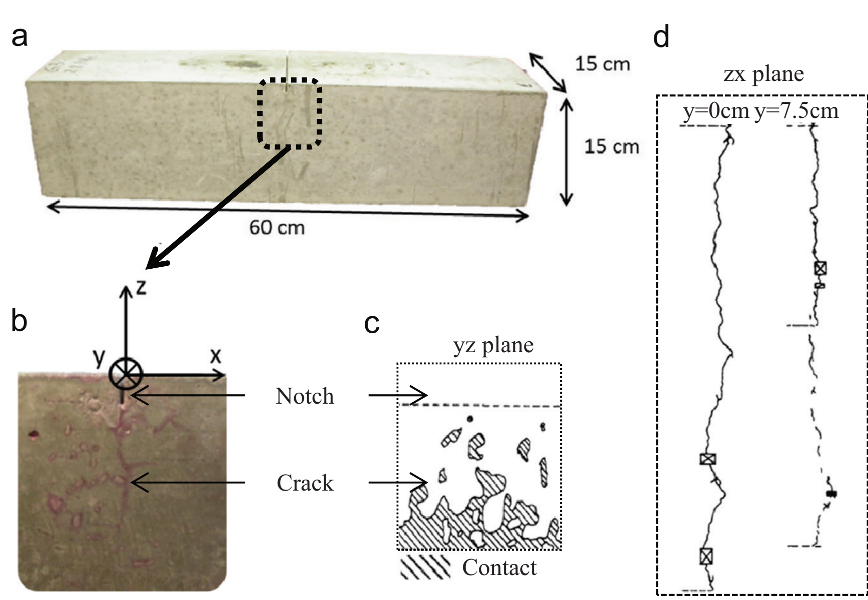

Fig. 1. Map of a real crack in concrete: (a) concrete samples used in the present study, (b) zoom on the crack region revealed by dye penetrant inspection at the surface (present study), (c) crack observation from [15] in a longitudinal plane at $y=0$ (surface) and $y=7.5$ cm (center), and (d) transverse observation at $x=0$ from [15].