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Numerical investigation of the effect of heterogeneity on the attenuation of shear waves in concrete

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ABSTRACT

Although ultrasonic transducers that emit horizontal shear waves are widely used in practice, no investigation has been conducted to study the attenuation of shear waves in concrete due to scattering by aggregates and air voids. Horizontal shear waves preserve more energy in comparison with longitudinal waves when propagating in concrete in low frequencies. However, the lower wavelength of shear waves increases the potential of their scattering attenuation in concrete. In this paper, we developed a 3D numerical tool and used it to study the scattering attenuation of horizontal shear waves in concrete in the 20–150 kHz frequency range. We showed that the scattering attenuation in this frequency range strongly depends on the size and material properties of aggregates. The shape of the aggregates and the presence of air voids slightly affected the scattering attenuation.

1. Introduction

Concrete has been one of the most used construction materials in the world, and monitoring the integrity of these structures is becoming more crucial due to the aging of the infrastructures made of this material. Nondestructive testing (NDT) allows the evaluation of the health of structures without causing any damage. Ultrasonic nondestructive testing allows the visualization of major discontinuities in acoustic impedance in deeper depths in the test specimens [1–3]. Therefore, they are appropriate for visualizing cracks, rebars and cavities.

The emergence of dry point contact (DPC) transducers has made ultrasonic NDT of concrete members more efficient by eliminating the need for coupling agents for the transmission of energy to the test specimens. Data acquisition systems integrating multiple DPC sending and receiving transducers have further increased the efficiency of collecting data [4]. These systems provide a large amount of data in a fraction of a second. Development of DPC transducers emitting horizontal shear waves offered a significant advancement in NDT of concrete structures. While most of the energy of longitudinal signals converts to shear and surface waves after transmission [4], horizontal shear waves preserve a higher level of energy while propagating in concrete, and therefore, permit greater penetration depth. The lower wavelength of shear waves in comparison to longitudinal waves and higher energy level of shear waves permit detection of smaller inclusions and defects at deeper depths in low frequencies. This technology is extensively used in practice to measure thickness and to detect rebar, delamination, and damage [5–12].

The main challenge in ultrasonic NDT of concrete structures is the composite nature of concrete. The heterogeneity of concrete can cause scattering of propagating ultrasonic waves [13]. Scattering attenuates the energy of the coherent waveforms (scattering attenuation) and limits the penetration depth of the ultrasonic waves. Scattering attenuation is correlated with the ratio of the aggregate size to the wavelength of the transmitted wave [13]. The velocity of shear wave in concrete is about 2500 m/s, while the velocity of longitudinal wave is around 4300 m/s [2]. The lower wavelength of shear wave in the hosting medium ($\lambda = c/f$, where λ is wavelength, $c$is velocity and f is frequency) increases the potential of scattering of shear waves in concrete. Due to the broad applications of data acquisition systems that employ DPC shear transducers in practice, and since the signal to noise ratio (SNR) plays a significant role in the detection of inclusions and defects, as well as geometry measurements, gaining insight into the scattering attenuation of horizontal shear waves is vital. Several numerical and experimental investigations have been conducted to understand the scattering attenuation of longitudinal waves in concrete [14–18]; however, to our knowledge, the literature lacks a study on the scattering attenuation of shear waves.

In this study, we used numerical simulations to study the effect of shape, size and material properties of aggregates on the scattering attenuation of shear waves in concrete. We used a simple approach to

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generate non-overlapping aggregates and voids and considered them in numerical simulations to investigate the influence of heterogeneity on attenuation of shear waves in concrete. Because the frequency range of 20–150 kHz is generally used in practice [2], we studied the scattering attenuation in this frequency range. To investigate the effect of shape and material properties of aggregates, we assumed that the aggregates could be ellipsoidal, representing rounded aggregates, or rectangular cuboid, representing angular aggregates, in shape and can have two different material properties. Furthermore, we considered synthetic concrete specimens with and without air voids to investigate the effect of porosity on the scattering attenuation. Because the range of application of ultrasonic testing is broad, it can be applied to concrete pavements, bridges, tunnel linings, foundations, etc., and since the maximum aggregate size in these structures can be different, we chose the maximum aggregate sizes of 18, 25, and 38 mm in the mix design of the synthetic concrete specimens to investigate the effect of aggregate size on scattering attenuation. We performed the same simulations for longitudinal waves and compared the scattering attenuation of shear and longitudinal waves in the synthetic concrete specimens. To perform the numerical simulations, we developed a 3D numerical tool. We used the finite integration technique (EFIT) [19] for the spatial discretization of the governing equations. We employed perfectly matched layers to truncate the computational medium. It is worth mentioning that the accuracy of the EFIT in simulating the propagation of waves in a concrete medium was shown in [14,15]; we do not validate EFIT in this paper.

The rest of the paper is arranged as follows. First, we discuss the methods introducing the EFIT, giving the formulation of the perfectly matched layer, and presenting the approach used to generate the non-overlapping aggregates. Next, we present the simulation results and discussion.

2. Methods

2.1. Elastodynamic finite integration technique

We developed a numerical tool to simulate wave propagation in concrete. FORTRAN was used for programming, and Elastodynamic Finite Integration Technique (EFIT) for spatial discretization of the differential equations. To use EFIT for discretization, Cauchy's equation of motion (Eq. (1)) and Hook's law (Eq. (2)) are written in terms of velocity and stress:

$$\rho \dot{v}_i = \sigma_{ij,j}, \tag{1}$$

$$\dot{\sigma}_{ij} = \lambda \delta_{ij} v_{k,k} + \mu v_{i,j} \tag{2}$$

where ρ is mass density, σ_{ij} are stress tensor components, v_i are velocity components, and λ and μ are Lamé constants. EFIT integrates the governing equations over each integration cell:

$$\int_{V_c} \rho \dot{v}_i dV = \int_{\partial V_c} \sigma_{ij} n_j dS, \tag{3}$$

$$\int_{V_c} \dot{\sigma}_{ij} dV = \int_{\partial V_c} (\lambda \delta_{ij} v_k n_k + \mu v_i n_j) dS. \tag{4}$$

The discretization is performed by estimating Eqs. (3) and (4) over the cell volume and boundaries using a one-point Gaussian quadrature rule. Here, we assume that the cells are cubic in shape and they have the same size. The arrangement of stress and velocity components in 3D is shown in Fig. 1 [15]. Note that in this study $\Delta x = \Delta y = \Delta z$. Velocity and stress components are located at different spatial places (Fig. 1). These components are located in the center of the corresponding integration cells. Material parameters of the heterogeneous concrete are defined on a spatial grid that matches the grid representing the center of σ_{ii}cells. A special averaging is used to estimate the material parameters at the location of velocities and shear stresses [20,21]. A Leap-frog scheme is used for time integration (Eqs. (5) and (6)):

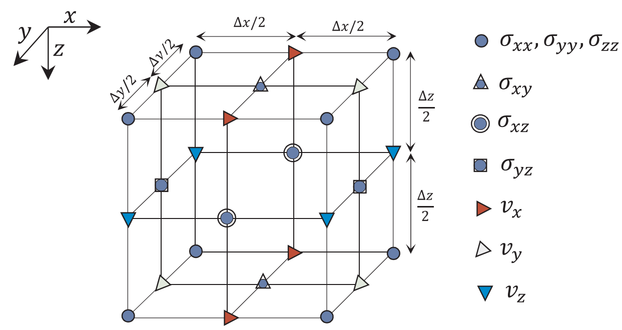

Fig. 1. Arrangement of stress and velocity components in EFIT.

$$v_i^{m+1/2} = v_i^{m-1/2} + \dot{v}_i^m \Delta t, \tag{5}$$

$$\sigma_{ij}^{m+1} = \sigma_{ij}^m + \dot{\sigma}_{ij}^{m+1/2} \Delta t. \tag{6}$$

To minimize the numerical dispersion, the following expression should be satisfied [21]:

$$max \ \ (\Delta x, \Delta y, \Delta z) \le \frac{1}{8}\lambda_{min} = \frac{1}{8}\frac{c_{min}}{f_{max}} \approx \frac{1}{10}\frac{c_{s,min}}{f_{max}}, \tag{7}$$

where c_{min} is the minimum wave speed in the medium, $c_{s,min}$ is the minimum shear wave speed in the medium, and f_{max} is the maximum frequency in the spectrum of the emitted signal. To avoid numerical instability, Eq. (8) has to be fulfilled [19].

$$\Delta t \le \frac{1}{c_{max}\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}}, \tag{8}$$

c_{max} in Eq. (8) is the maximum wave speed in the medium. Assuming that $\Delta x = \Delta y = \Delta z$, Eq. (8) can be simplified to Eq. (9).

$$\Delta t \le \frac{\Delta x}{\sqrt{3}\, c_{max}}. \tag{9}$$

It is worth mentioning that EFIT is virtually the same as a second-order velocity-stress finite difference on a staggered grid. Higher order finite difference methods allow using a coarser spatial grid, but a fine spatial grid is required for representing the strong heterogeneity of concrete. Therefore, EFIT is the most efficient technique for the simulation of wave propagation in this material.

2.2. Implementation of perfectly matched layers

Perfectly matched layers (PML) [22–24] were implemented in the program and assigned to the boundaries with faces perpendicular to the x and y-directions to truncate the computational domain laterally (Fig. 2).

The amplitude of the outgoing waves decays exponentially in the PML by employing a damping profile. The value of damping at the interface of the medium and absorbing layer is zero in the perfectly matched layer, material properties of PML and computational medium match perfectly in the interface, and as moving into the absorbing layer the damping is gradually increased. A fixed boundary condition can be assigned to the outer boundary of a perfectly matched layer. The layers have to be thick enough to dampen virtually all of the energy of the outgoing waves. Here, we implemented the formulation for PML given in [24]. To facilitate use of formulation, we present the equation of motion (Eq. (10)) and constitutive equation (Eq. (12)) in the perfectly matched layers for an isotropic media. θ and ζ in Eqs. (10) and (12) are called memory variables which are evaluated from Eqs. (11) and (13). The equations after time integration using leap-frog scheme are shown:

$$\rho v_i^{m+1/2} = \rho v_i^{m-1/2} + \Delta t\left(c_p \delta_{jp} \sigma_{ij,j}^m + (1-\delta_{jp})\sigma_{ij,j}^m + d_p \theta_i^{m-\frac{1}{2},p}\right), \tag{10}$$