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Ultrasonic tests in the evaluation of the stress level in concrete prisms based on the acoustoelasticity

Karen F. Bompan *, Vladimir G. Haach

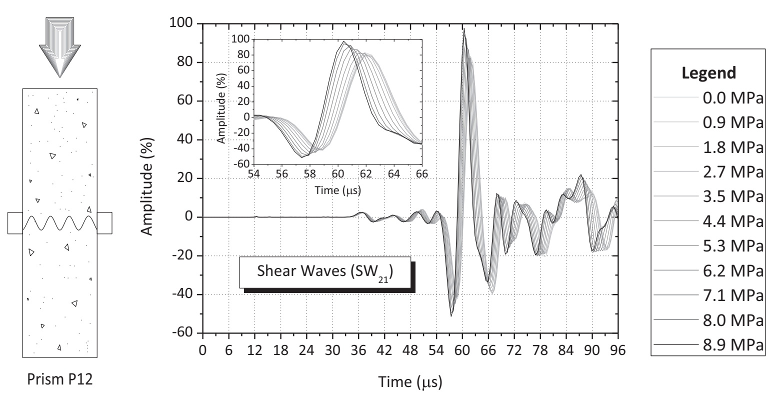
School of Engineering of São Carlos, University of Sao Paulo, Av. Trabalhador Saocarlense, 400, 13566-590 Sao Carlos, SP, Brazil

HIGHLIGHTS

- Velocities of ultrasonic waves are influenced by stress state of the concrete.
- Ultrasonic waves polarized in the loading direction are more sensitive to stress.
- The acoustoelastic constants and the properties of the concrete are related.
- The ultrasonic tests showed potential to evaluate the stress state in concrete.

GRAPHICAL ABSTRACT

The study of the acoustoelastic behavior of the concrete represents an advance in direction to the evaluation of stress state using the ultrasound.



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ABSTRACT

The ultrasonic pulse velocity method is a nondestructive test commonly used for the determination of the elastic properties of materials and verification of non-homogeneities and damages in structural elements. Another application for the ultrasound is the measurement of the stress state in a material. However, the use of ultrasonic waves for the latter purpose has been poorly studied, mainly regarding application in concrete structures. This paper addresses the use of ultrasound for the evaluation of stresses in concrete structures. Uniaxial compression tests were performed on concrete prisms. During the tests, longitudinal and shear ultrasonic waves were emitted to specimens subjected to different compressive stress levels. The results showed the increase of compression stress leads to higher velocities of ultrasonic waves, which proved the acoustoelastic effect. Such behavior was not observed in longitudinal waves emitted perpendicularly to the direction of the stress application. The largest increase in velocity was observed for longitudinal waves propagating in the same direction of the load application (variations on the order of 1%). Acoustoelastic coefficients were determined for each tested prism, according to the change in the velocities of the ultrasonic waves. The present study contributed to the knowledge on the acoustoelastic behavior of the concrete elements and shows the potential of ultrasonic tests to evaluate the stress state in concrete structures.

* Corresponding author.
E-mail addresses: kbompan@usp.br (K.F. Bompan), vghaach@sc.usp.br (V.G. Haach).

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1. Introduction

Concrete structures are in constant deterioration and require regular maintenance routines. Tests are commonly applied for the evaluation of their actual conditions and definition of effective interventions, so that the service life can be extended. Nondestructive tests (NDT) are interesting tools, since they produce insignificant or no damages to the evaluated elements [1]. Ultrasonic pulse velocity (UPV) is a nondestructive test that consists in the emission of high frequency waves (above 20 kHz) that propagate through a tested element [2,3]. It is commonly used for the verification of homogeneity, damages and determination of the elastic properties of materials [4–12]. A potential underexplored application of ultrasound consists in its use for the evaluation of a stress state in a structure. This application is based on the acoustoelasticity theory, which shows that the velocity of propagation of a mechanical wave and the stress state in a material are related [13]. Thereby, a change in the stress level causes variation in the waves velocity, which is a phenomenon called acoustoelastic effect. Hughes and Kelly [14] developed equations for representing the acoustoelastic effect in isotropic materials based on the Murnaghan's theory for finite deformations [15] and nonlinear elasticity. Eqs. (1)–(5) show the velocities of longitudinal and shear waves along the principal directions of an isotropic solid subjected to a state of uniaxial stress.

$$\rho V_{11}^2 = \lambda + 2G + \frac{\sigma_{11}}{3K}\left[2\ell + \lambda + \frac{\lambda + 2G}{G}(4m + 4\lambda + 10G)\right] \tag{1}$$

$$\rho V_{12}^2 = \rho V_{13}^2 = G + \frac{\sigma_{11}}{3K}\left[m + \frac{\lambda n}{G} + 4\lambda + 4G\right] \tag{2}$$

$$\rho V_{22}^2 = \rho V_{33}^2 = \lambda + 2G + \frac{\sigma_{11}}{3K}\left[2\ell - \frac{2\lambda}{G}(m + \lambda + 2G)\right] \tag{3}$$

$$\rho V_{21}^2 = \rho V_{31}^2 = G + \frac{\sigma_{11}}{3K}\left[m + \frac{\lambda n}{4G} + \lambda + 2G\right] \tag{4}$$

$$\rho V_{23}^2 = \rho V_{32}^2 = G + \frac{\sigma_{11}}{3K}\left[m - \frac{\lambda + G}{2G}n - 2\lambda\right] \tag{5}$$

$$K = \lambda + \frac{2}{3}G \tag{6}$$

In the equations, σ_{11} is the normal stress applied to axis 1, ρ is the density of the material, m, n and ℓ are Murnaghan's elastic constants, λ is the Lamé's first parameter, G is the dynamic shear modulus or Lamé's second parameter and K is the volumetric modulus (Eq. (6)). Wave velocities are represented by the variables V_{11}, V_{12}, V_{22}, V_{21} and V_{23}, where first and second indexes indicate the axis of wave propagation and polarization, respectively. Therefore, equals indexes are used to designate longitudinal wave velocities, whereas different ones denote shear wave velocities.

According to Lillamand et al. [16], Eqs. (1)–(5) can be linearized, which results in Eq. (7), where V_{ij}^{σ} and V_{ij}^{0} are the wave velocities in a medium with and without a uniaxial stress, respectively, and A_{ij} is the acoustoelastic constant (i and j = 1, 2 or 3). Eq. (7) shows a linear relationship between the relative variation of the wave velocity and the uniaxial stress applied to material. Therefore, the acoustoelastic constant is the angular coefficient.

$$\frac{V_{ij}^{\sigma} - V_{ij}^{0}}{V_{ij}^{0}} = A_{ij}\sigma_{11} \tag{7}$$

Based on the acoustoelastic effect, some researchers have studied the possible use of the ultrasound in the assessment of the stress state in materials. Wei et al. [17] evaluated the propagation of Rayleigh surface wave in polymethylmethacrylate subjected to a homogeneous stress and observed a linear dependence between the wave velocity and the static stress applied. Under laboratory conditions, Chaki and Bourse [18], determined the tensile stress in prestressed steel strands using ultrasonic waves propagation and acoustoelasticity theory. Kleitsa et al. [19] and Aggelis et al. [20] discussed the possible assessment of the stress value present in steel strands used in ground anchors by ultrasonic measurements in the anchor head. Both studies conducted experimental and numerical analyses and concluded the propagation of shear waves provided better results than the propagation of longitudinal waves. Egle and Bray [21] evaluated the potential use of the acoustoelastic effect for the measurement of residual stresses in railroad steel and observed the experimental data were consistent with the theory presented by Hughes and Kelly [14]. Kamyshev et al. [22] also measured residual stresses in railway vehicle wheels using ultrasound and confirmed the reliability of the data by a destructive method.

Regarding concrete structures, few studies on the use of acoustoelastic effect for the evaluation of stresses have been developed. Lundqvist and Rydén [23] evaluated the influence of the prestress level on the frequency and vibration modes of concrete beams based on acoustoelasticity. They observed an increase in the vibration frequencies with the increase in the prestressed level and demonstrated that such behavior can be predicted by a non-linear finite element model based on Murnaghan's theory. One of the first studies on the effect of stresses on ultrasonic tests was carried out by Popovics and Popovics [24]. The authors conducted an experimental program in concrete cylinders subjected to gradual increasing loading and measured the longitudinal ultrasonic velocity transversally to the loading axis. They concluded the pulse velocity is independent of stress level in practical terms. On the other hand, Lillamand et al. [16] studied the influence of stress on the ultrasonic waves propagated longitudinally and transversally to the loading axis during compressive tests on cylindrical concrete specimens. They observed the longitudinal and shear waves polarized along the loading direction were more sensitives to stress level and concluded the stress level in concrete can be evaluated by ultrasonic tests, however, it is hampered by the wave scattering. Payan et al. [25] propose a method, originally from geophysics, which analyzes coda waves for stress evaluation in concrete through ultrasonic tests. The method provided promising results and enabled to measure the nonlinear elastic coefficients.

The definition of a reliable method to evaluate stresses in concrete structures using ultrasonic tests will create several new applications for this NDT. However, before this stage a large discussion should be addressed on the acoustoelastic behavior of concrete. Therefore, the main objective of this research is to quantify the stress level in concrete prisms subjected to compression loading based on acoustoelastic effect using ultrasonic tests with the propagation of longitudinal and shear waves.

This paper investigates the acoustoelastic behavior in different concrete prisms using the ultrasonic pulse velocity test. In the first section, the experimental program is presented describing the test specimens, the properties of the materials used to construct the concrete specimens with different compositions and the procedures used in the ultrasonic tests. Next, the results are discussed showing the variations on the behavior of the longitudinal and shear waves with the increase of the stress applied to the concrete prisms. The acoustoelastic coefficients are calculated and their variations with the mechanical properties of the concrete prisms are discussed. Finally, the conclusions are provided indicating the main goals of this research.