Construction and Building Materials 119 (2016) 61–70

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Qualitative assessment of concrete by ultrasound tomography

Vladimir G. Haach *, Fernando C. Ramirez

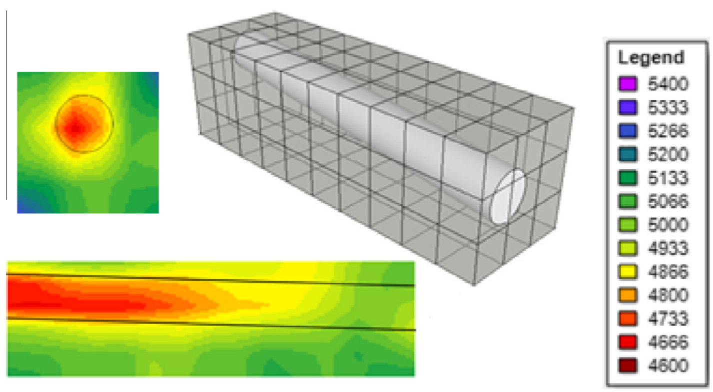
School of Engineering of Sao Carlos, University of Sao Paulo, Av. Trabalhador Saocarlense, 400, 13566-590 Sao Carlos-SP, Brazil

HIGHLIGHTS

- Ultrasonic tomography was more efficient than conventional ultrasonic tests.
- A large number of measurements not necessarily returns better images.
- The compressive strength decrease caused a slight reduction in the velocities.
- Images quality depends on the size and arrangement of transducers.
- Ultrasonic tomography has shown a powerful tool for the assessment of concrete.

GRAPHICAL ABSTRACT

Ultrasonic tomography has shown a powerful tool for the assessment of the homogeneity of concrete elements and detection of heterogeneities.



ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form 21 March 2016
Accepted 6 May 2016
Available online 13 May 2016

Keywords:
Ultrasonic tomography
Non-destructive test
Damage detection
Concrete

ABSTRACT

Ultrasonic tomography is a non-destructive method that enables the mapping of an internal section of a structure from multiple projections for the identification of discontinuities and/or damages. This study addresses the application of the ultrasonic tomography method for the qualitative assessment of concrete. Several experimental tests with variations in concrete composition, presence of voids, arrangement and frequency of transducers were conducted on concrete prisms. The results show the ultrasonic tomography was more efficient than conventional ultrasonic tests. Analyses of several transducers arrangements revealed a large number of measurements not necessarily returns better images. The great potential of the ultrasonic tomography technique for the evaluation of homogeneity and detection of discontinuities and damages of concrete structures has been confirmed.

1. Introduction

Concrete is a key piece in the construction industry and several worldwide engineering projects, such as roads, airports, dams, bridges, buildings, among others, are continuously subject to effects that degrade their structural integrity (Mehta and Monteiro [1]). There has been a growing concern on the state of deterioration and safety of such structures, therefore, alternatives for an effective and reliable assessment of their quality must be developed. In this sense, the use of Non-Destructive Testing (NDT) constitutes an interesting strategy for the monitoring and assessment of the state of concrete structures without harming their appearance or performance, see Hoła and Schabowicz [2].

* Corresponding author.
E-mail addresses: vghaach@sc.usp.br (V.G. Haach), fedkam86@hotmail.com (F.C. Ramirez).

http://dx.doi.org/10.1016/j.conbuildmat.2016.05.056

Non-destructive tests with ultrasound are based on the propagation of high frequency waves (above 20 kHz) through an analyzed element and have been widely applied to concrete structures (Philippidis and Aggelis [3], Panesar and Chidiac [4], Lai et al. [5]). The speed of the propagation of stress waves (v) depends on the density (ρ) and elastic constants of the solid (elastic modulus, E and coefficient of Poisson, μ – see Eq. (1) for isotropic materials) and its main applications are related to the detection of damages and evaluation of relative conditions of concretes.

$$v^2 = \left(\frac{E}{\rho}\right)\left(\frac{1-\mu}{(1+\mu)(1-2\mu)}\right) \tag{1}$$

Basically, two different conventional methodologies, namely through-transmission and pulse–echo have been applied to ultrasonic tests (Malhotra and Carino [7]). In both methods, an ultrasonic pulse is transmitted at a point on the tested object. In the through-transmission method, also known as Ultrasonic Pulse Velocity (UPV), the travel time is measured at another point on the object by a receiver, whereas in pulse-eco, the reflection (echo) of the ultrasonic pulse in flaws or interfaces is measured by the same or other transducers acting as receivers. ACI 228.2R-13 [6] has established test procedures, instrumentations and data analyses for such stress-wave methods applied to concrete structures.

Any variation in the speed of propagation of stress waves indicates voids, non-uniformity of the material or damages. Whitehurst [8] published a classification proposal for normal concretes of approximately 2400 kg/m^3 density based on pulse velocity as an indicator of quality (Table 1). However, the author [8] claimed a better approach would involve comparisons with regions of the structure known to be of acceptable quality. Nevertheless, according to Carino [9], inexperienced investigators often use only this classification for the interpretation of tests results.

As pointed out by Popovics [10], ultrasonic pulses can be affected by several factors, as surface condition, moisture, presence of reinforcements and mainly composition of concrete. Such factors cause variations in the speed of propagation of ultrasonic waves from a structure to another even for intact concrete, which hampers the interpretations of results. Abo-Qudais [11] studied the effect of concrete-mixing parameters on the propagation of ultrasonic waves and observed the heterogeneity of the concrete structure generates scattering of ultrasonic waves, since the transition zones between aggregates and hydraulic cement paste tend to reflect part of the waves. The ultrasonic tomography considerably enhances the performance of conventional ultrasonic tests, as it creates sliced images of a structure, called "tomograms" through the combination of several measurements, which enables the identification of locations, shape and size of material discontinuities (Schabowicz [12], Schabowicz and Suvorov [13], Gorzelanczyk et al. [14]).

Ultrasonic tomography is one of the most complex applications of the ultrasound wave propagation method. It combines several measurements of velocity of propagation of ultrasonic waves taken from different intersecting paths inside the material. The projections are used in the reconstruction of a map of velocities for the detection of discontinuities and damages. Martin et al. [15] and Muldoon et al. [16] explored the application of ultrasonic tomography and conducted tests in prestressed beams for the identification of internal voids in tendon ducts. Aggelis and Shiotani [17] applied the ultrasonic tomography technique to evaluate the repair of a crack on a beam of a bridge of reinforced concrete using the spreading of Rayleigh waves. Molero et al. [18] studied the use of ultrasound images for the evaluation of concrete subjected to freeze-thaw cycles. Ferraro et al. [19] used tomograms to assess the integrity of full-scale bridge piers before and after impact tests. In all cases, the tomography technique detected damages inside the structure that were not visually apparent. Images showed clear variations in the velocities of ultrasound pulses and specific regions could be identified, at low or high velocities, and indicated voids or damages in the first case and reinforcements in the last case, respectively. More recently, Hoegh and Khazanovich [20] performed a quantitative nondestructive characterization of defects and inclusions in Portland cement concrete structures via extended reconstructions for linear array ultrasound systems. The authors used 50-kHz dry point contact transducers and locating inclusions of a diameter as small as 18 mm.

This paper addresses a qualitative assessment of concrete through 3D ultrasonic tomography. Some aspects of the technique are discussed on a first experimental program. In a second phase, variations in the speed propagation of ultrasonic waves in concrete prisms of different compositions are analyzed and compared to compressive strength values. In a third phase, prisms with discontinuities are evaluated, so that the main differences between measurements performed in damaged and non-damaged elements can be discussed.

Table 1
Qualitative assessment of concrete by the UPV method.

Velocity (m/s)	Concrete condition
4575 and above	Excellent
3660–4575	Good
3050–3660	Regular
2135–3050	Poor
Below 2135	Very poor

2. Ultrasonic tomography theory (travel-time concept)

The principle of image reconstruction is based on the evaluation of a series of projections of measurements taken from different angles. In practice, this procedure estimates the real image of the object under study; however, the fidelity of the reconstruction depends on the acquisition process and pre-processing of the data through mathematical reconstruction methods. The main procedures applied for the generation of tomographic images can be categorized into filtered back-projection and iterative reconstruction techniques. Most filtered back-projection approaches are based on the use of the Radon transform (Gullberg et al. [21], Koshovyi et al. [22], Khan and Chaudhuri [23]), whereas the iterative reconstruction techniques are based on the resolution of a system of algebraic equations generated from an array of measurements (Kwon et al. [24], Yanli [25], Chai et al. [26], Aggelis et al. [27], Chai et al. [28]).

The basic concept used in this study is the transformation of each travel-time measured into different paths (Δt_j) as sums of partial travel-times $(\Delta t_i)_j$ in all elements of a defined mesh, as shown in Eq. (2), see Fig. 1.

$$\Delta t_j = \sum_i (\Delta t_i)_j \tag{2}$$

The travel–time of an ultrasonic wave in a specific element of a mesh can be calculated by the definition of velocity (v_i), see Eqs. (3) and (4), where $(w_i)_j$, is the length of the j-path in the i-element. Therefore, the group of all measurements generates a system of linear equations (see Eq. (5), whose solution is a map of velocities, or slowness (s_i). Such a map can be related to the elastic constants of the material and enables the detection of discontinuities and damages in the specimen under evaluation.

$$v_i = \frac{(w_i)_j}{\Delta t_i} \quad \rightarrow \Delta t_i = \frac{(w_i)_j}{v_i} \tag{3}$$