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Ultrasonic signal modality: A novel approach for concrete damage evaluation

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A B S T R A C T

In this paper, a new approach for characterizing material damage, using ultrasonic waves, is proposed. Two concrete series with two types of cement with different C_3A content and similar mechanical properties were subjected to external sulphate attack (ESA) and evaluated using a novel Recurrence Plot Quantification Analysis (RQA) method. This brand new technique was compared with several methods, such as mechanical tests (compressive and flexural strength determination), dynamic test (dynamic modulus) measurements, and traditional ultrasonic measurements (propagation velocity and ultrasonic wave attenuation). In these experiments, RQA showed a high sensitivity to damage in spoiled series, improving the reliability of damage detection with ultrasonics in non-homogeneous materials compared to other non-destructive techniques. Interesting advantages of this new non-destructive technique are: a) the RQA parameter is normalized (range of 0 to 1); b) a calibration process is not required; c) the values of its standard deviation show the dispersion of the damage. It can contribute greatly to the diagnosis of the degree of damage to a material, when combined with other traditional measures such as the attenuation of the material.

1. Introduction

Concrete is the most widely used synthetic material all over the world in civil and building engineering and architecture. It is composed of water, cement, gravel and sand mixed in different proportions depending on the kind of mechanical and physico-chemical properties required by the project. This material has an excellent mechanical and structural performance. However, it has important issues in terms of durability when exposed to different environments and harsh conditions. Freeze-thawing cycles, internal sulphate attack (ISA), external sulphate attack (ESA), overload cracking and wet-drying cycles are some of the processes which require early damage detection in order to avoid serious problems involving the structural elements made with concrete.

Of all the problems previously mentioned, in the present research, ESA was selected to damage the concrete, due to its micro-cracking and expansive process (produced by the formation of secondary ettringite), which globally affects the cement paste structure, weakening the different interfaces, and consequently reducing the physical and mechanical integrity of the material. Initially, this sulphate bearing product fills the voids and capillary network, as well as promoting an increase in the compressive strength [1]. When the voids and free space in the binding matrix are full, micro-cracks start to appear and the compressive strength and Young's modulus of the concrete decrease. When this process is highly aggressive, the cement paste could lose strength and adhesion capacity due to decalcification of C-S-H [2]. Due to the aggressive action of ESA, premature and accurate detection of the spoiling of concrete elements has become an important issue for many research projects.

Damage characterization techniques can be classified into either local or global methods. It is believed that these two methods should be used in a complementary way to effectively and correctly assess the integrity of a complex structure [3]. Most currently used techniques, such as visual, acoustic, magnetic field, and electrical, are effective yet local in nature [4,5]. They mainly require that the vicinity of the damage is known a priori and the portion of the structure being inspected is readily assessible. Methods like Electrical Resistance Tomography have been recently investigated showing high sensitivity to discrete cracks and heterogeneties from different natures like iron bars or discrete cracks performed with plastic plates [6,7]. On the other hand, global methods quantify the healthiness of a structure (or part of it) by examining changes in its vibrational characteristics or changes in

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ultrasonic waves propagation. The standard method for detecting defects within a concrete structure involves the use of drilled core samples [8]. Some of the traditional methods are strength tests, three point bending tests and, the determination of the elastic modulus. These methods are the most immediate approaches, but have the disadvantage of being expensive and allowing the analysis of only a small portion of the structure. Hence, there is a need for nondestructive research methods in the field of material characterization and damage detection. Owing to the non-invasive nature, Non Destructive Test (NDT) techniques appear as a reliable tool to detect and characterise damage of different typology. Recent studies are focused in detecting nonlinearities in mechanical waves in cementitious materials due to the sensitivity to damage either with vibration spectroscopy and ultrasonics. Nonlinear Elastic Wave Spectroscopy techniques are based on the nonlinear decreasing of the fundamental frequency with the increasing amplitude of excitation. With this techniques, thermal damage, alkali-silica reaction, sulphate attack and other distributed damages in concrete have been successfully monitored [9–12]. Acoustic Emission techniques also exhibited good results detecting the focus of micro-cracking process and flaws location when energy is released during mechanical tests [13,14].

Because of its heterogeneous nature, concrete contains micro-defects even before the occurrence of any damage. Therefore, ultrasonic waves traveling through concrete are both modulated and attenuated as a consequence of the material's inhomogeneity. In addition, scattering occurs at each interface between the aggregate and the matrix [15]. Thus, the travelling waveform exhibits a decrease in amplitude due to the scattering process at each matrix–aggregate interface. The most common ultrasonic measurements are the propagation velocity (ultrasonic pulse velocity, UPV) and the ultrasonic waveform attenuation introduced by the material, both based on the linear theory of the propagation signal (the frequency components of the emitted pulse and the received pulse are similar). Recent studies contributed to exploit the information of UPV with ultrasonic imaging and travel wave tomography to characterise mechanical and freeze-thaw cycles damage [16,17]. However, the presence of nonlinear terms in the elastic response of a granular medium is considered an indicator related to the presence of any kind of damage. Many techniques have been presented to extract nonlinear features from ultrasounds based on many different approaches, such as higher-order harmonics [18], subharmonics [19], or sidebands [20]. Nonlinear ultrasonics are also being studied by the Scaling Substraction Method, a novel technique that allows to correlate damage with the loss of linearity based on amplitude scaling in a through-transmission layout [21,22]. Also, ultrasonic surface wave has been used to detect global micro-cracking processes in concrete elements [23,24], even with air-coupling layout [25].

In the present paper, a new signal modality approach for material characterization is presented. When considering the characterisation of the signal modality, we adhere to the changes in the nature of real world signals: the degree of sparsity, nonlinearity, stochasticity, etc. The applications of signal modality characterisation have only recently become apparent in signal processing and machine learning and are a key topic of multidisciplinary research [26]. In the case at hand, the concept is applied to analyse the interaction between the injected ultrasonic wave and the nonlinear scatters placed at the concrete specimen under study. Fig. 1 illustrates a typical ultrasonic inspection where the input signal has a predominant deterministic component (coherent component) and the output is the sum of many superimposed echoes scattered by the heterogeneous microstructure of the material (incoherent components). The resulting stochastic nature of the received signal comes not only from the randomly placed reflections, which cause significant changes in amplitude, but also from the echoes transmitted by nonlinear coupling, which combine with different initial phases. Measuring the degree of predictability of the received signals can give information about how the coherent and incoherent components are combined as a function of the inner microstructure and, thus, about the internal damage. The aim of the proposed method is to provide a quantitative measure of the growth of the damage, assessing any change in the material integrity as a whole. The results obtained from some concrete specimens exposed to an ESA attack are analysed and discussed in order to make an initial assessment of the performance of the new proposed measurement method.

The remainder of this paper is organized as follows. The new approach based on the signal modality characterization is discussed in Section 2. Section 3 presents experimental issues, the tested materials as well as the traditional ultrasonic measurements carried out to characterize them. Section 4 describes the results obtained from the application of destructive tests and the ultrasonic measurements to the specimens under testing. The results of the predictability are discussed and compared to the previously known techniques. Finally, the conclusions are summarized in Section 5.

2. Recurrence Plot Quantification Analysis (RQA)

An ultrasonic wave has numerous interactions with the internal structure of the material and the data derived from such observations is related to the behaviour of the material at different structural scales (from the macro- to the micro-level). The concept of multi-scale interactions can be described starting at the level of atomic bonds, its nanometric scale (gel pores, the capillary net mainly made of portlandite and calcium aluminate hydrates), and including that of the mesoscopic (microscopic and millimetric) structure, the aggregate dimension, and finally the concrete structure as a single component [27]. The advantage of ultrasonic waves is that they allow access to every level of these interactions by changing the injected frequency, thereby providing a reliable means of characterising the material at each scale.

The new proposed technique aims to quantify the non-coherent waves produced by echoes from the edges and faces of the specimen, as well as the effects of scattering from the aggregates. Both the echoes and the scattering effects strongly depend on the structural scale, and therefore on the working frequency. In particular, the scattering component of the global attenuation of the ultrasonic wave is well-known to be determined as a function of the input frequency (or its corresponding wavelength, λ) and the average size of the aggregates ($\overline{D}$). Three different regions have been identified: the Rayleigh field ($\lambda \ll \overline{D}$), the stochastic field ($\lambda \simeq \overline{D}$), and the geometric field ($\lambda > \overline{D}$) [28]. The stochastic component that appears depends on the aforementioned ratio and, somehow, summarizes the inhomogeneities seen at the analysed scale and present in the specimen under study. Quantifying the degree of predictability of the time series based on the concept of characterization of the modality of the signal [29] can provide information about the signal strength of the input deterministic component in relation to the whole of the acquired time series.

The study of a deterministic signal has relied on the concept of phase space, which is a vector space that collects all the possible system states that are useful for determining the future evolution of the signal. For a time series $x(n)$, the phase space would be defined by

$$\overrightarrow{X_n} = [x(n), x(n-\tau), ..., x(n-(E-1)\cdot\tau)]^T, \quad n=1, ..., N-(E-1)\cdot\tau \tag{1}$$

where N is the total number of points, τ is the discrete time lag, E is the embedding dimension [30,31], and T refers to the transposed matrix. The proper selection of τ and E is crucial in the further analysis because it affects the correct representation of the data's evolution in time. A common approach to determining the value of τ is the one proposed by Fraser and Swinney [32], which uses the first null of the time delayed mutual information. The selection of the minimum embedding dimension E is based on the false nearest neighbour algorithm proposed by Cao [33]. In the present paper, the value of the embedding dimension E is chosen as the fraction of false points smaller than 2%. Any other methods [34] for the estimation of E and τ might be used and the results