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Nonlinear ultrasonic evaluation of load effects on discontinuities in concrete

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ABSTRACT

The presence of discontinuity surfaces in concrete structures, i.e. two or more layers in contact, may be an existing situation with evident relapses on damage formation and progression. Differences occur depending on the type of discontinuity, which could be a thin weaker layer or a pre-existing crack. The behavior of pre-existing interfaces is here studied by means of the Scaling Subtraction Method, a Nonlinear Ultrasonic Non-Destructive Technique, that revealed to be effective in describing the mechanical evolution of concrete samples with discontinuity surfaces under the effects of compressive loads.

1. Introduction

Discontinuity surfaces such as joints in large concrete structures are often indicated as weak areas where damage may begin to propagate from. Its progression appears in the form of increasing crack density [1] and/or growing crack openings [2,3], depending on the geometry of the structure considered and on loading conditions. In particular, damage mechanisms seem to differ depending on the nature of the discontinuity, i.e. an existing crack [4] or a weaker layer [5–7]. Both kinds of discontinuities are very common in concrete structures, often with severe consequences on their structural performances and durability.

Macroscopic cracks may be produced by unexpected loads, seismic events, subsidence phenomena, etc. [4]. Damage progression may easily take its starting point from the weak area thus created and its severity mainly depends on the crack size, opening and location.

Discontinuities in the form of a weaker material layer are also frequent in concrete structures. One only needs to think of interfaces between multiple castings [5] or patch repair works [6,7]: if no proper precautions are adopted, a typical deleterious consequence could be the formation of a thin low-quality layer at the interface between fresh and seasoned material. Again, the layer itself or the region close to it [8] can easily fail at load levels lower than expected.

In this paper, both a “crack-like discontinuity” and a “low-quality layer discontinuity” have been experimentally studied. Accordingly, two types of laboratory specimens have been produced: the first was made of two piled concrete cubes (the interface between the two cubes roughly simulating a macroscopic crack) and the second was made of two similar concrete cubes piled one on the other with the interposition of a thin layer of low-quality cement paste. A specific damage process was induced by means of compressive uniaxial load steps and its progression was analyzed by means of the Scaling Subtraction Method (SSM) [9,10], a Nonlinear Ultrasonic Non-Destructive Technique.

The same way as other well-established nonlinear ultrasonic methods, the SSM is concerned with the detection of nonlinear terms in the elastic response of a solid to a linear ultrasonic wave excitation. Among them, successive harmonic components [11–13], nonlinear attenuation [14], amplitude dependent phase delay [15], resonance frequency shift [16,17], modulated frequencies [18,19], multi-mode resonance spectroscopy [20] etc., are universally considered to be related to the presence of micro-cracks and/or to a deterioration of the material properties. Differently than most of the other filtering-based techniques [21], however, the SSM presents the advantage that no parameters are needed for the analysis and that the quality of the results is less affected by the increase of the distance between transducers and nonlinear scatterers [22]. In addition, as it will be shown in the following, the SSM makes it possible to account for nonlinear terms at the fundamental frequency, which in general have a relevant magnitude and allow to conduct experiments in a narrow frequency band, with a significant improvement of the signal-to-noise ratio.

For these reasons, and in consideration of its easy experimental implementation and complete non-destructiveness, the SSM turns out to be particularly attractive in view of its potential application for the on-site assessment of existing structures. Its effectiveness has already been demonstrated in evaluating damage occurrence in homogeneous concrete and mortar samples with experimental evidence [10].

Here we show that the SSM (discussed in Section 2) is a suitable technique to study the evolution of damage in proximity of

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discontinuity surfaces. Indeed, we prove it to be sensitive to very small changes in the nonlinearity of the sample and hence to the related damage evolution steps (Section 3.4). Furthermore, the validity of the approach is independent on the arrangement of the transducers, i.e. both direct and indirect transmission modes work equally well. Elsewhere, it has also been shown that the relative distance between damaged area and transducers is not a relevant issue [22]. Finally, we show that the evolution of nonlinearity at low load levels is different for the cases of a "low-quality layer discontinuity" and for a "crack-like discontinuity", while their behavior is very similar at large load levels (Section 4).

2. The Scaling Subtraction Method

The presence of elastic nonlinear portions of material in damaged media breaks the proportionality between input signals (i.e. the electrical signals, measured in Volts, proportional to a mechanical excitation, usually expressed as stresses) and output signals (i.e. the electrical signals proportional to the dynamic deformations in the medium due to the ultrasonic propagating wave, usually expressed as strains). The superposition principle is no longer applicable and the elastic response to an impinging ultrasonic wave contains nonlinear terms which show a dependence on the amplitude of the injected wave. The break of proportionality can be retraced to three main mechanisms [9,23]:

1. Nonlinear losses of elastic energy.
2. Redistribution of energy among the various generated frequencies.
3. Dependence on amplitude of the phase of the response.

The Scaling Subtraction Method (SSM) takes advantage of such break of proportionality in order to extract the signature of damage in an ultrasonic signal. In a very general treatment, when a nonlinear medium is excited by a sinusoidal monochromatic wave of amplitude A and frequency ω_0, the signal recorded after propagating through the sample can be written in terms of a Fourier Series:

$$v_A(t) = \sum_{n=1}^{\infty} B_n(A)\left[\cos(n\omega_0 t + \phi_n(A))\right]. \tag{1}$$

Notice that both the amplitude coefficients B_n and phases ϕ_n have a dependence on the amplitude A of the excitation. Nonlinear features are extracted from the signal in the form of Eq. (1) by means of a simple subtraction with a linear reference signal $v_{\mathrm{ref}}(t)$.

To define $v_{\mathrm{ref}}(t)$, it is reasonable to assume that when the sample is excited by a sufficiently low amplitude A_{lin}, nonlinear terms are negligible and the recorded signal, which can be experimentally measured, can be considered as the linear elastic response of the specimen:

$$v_{\mathrm{lin}}(t) = B_1(A \rightarrow 0)\cos(\omega_0 t + \phi_1). \tag{2}$$

Thus, the linear reference signal (v_{ref}) at a higher amplitude $A = kA_{\mathrm{lin}}$ ($k \gg 1$) can be constructed by applying the proportionality principle, valid if the system was linear. The elastic response expected from an equivalent linear sample would have been:

$$v_{\mathrm{ref}}(t) = kv_{\mathrm{lin}}(t) \neq v_A(t) \tag{3}$$

where v_A is the actual nonlinear signal at high amplitude, i.e. the one measured in the nonlinear sample.

Once the reference signal is defined by simply subtracting the linear reference of Eq. (3) to the nonlinear measured signal (which is in the form of Eq. (1)) one obtains an electric signal containing only the nonlinear response of the specimen, which will be denoted as the SSM signal:

$$w_A(t) = v_A(t) - v_{\mathrm{ref}}(t). \tag{4}$$

The SSM signal depends on the amplitude (A) of the injected wave. We stress here that the nonlinear signature in the SSM signal $w_a(t)$ takes into account not only higher order harmonics and sidebands (which may be present depending on the experiment), but also the nonlinear contributions at the fundamental frequency, such as nonlinear attenuation and phase shift, both normally cancelled by a filtering technique.

A quantitative parameter able to represent the nonlinear signature can be defined. In particular, the SSM indicator was introduced as the "energy" of the SSM signal $w_A(t)$:

$$\theta(A) = \frac{1}{T}\int_0^T w_A^2(t)dt \tag{5}$$

where T is a proper time window. Likewise, a variable that represents the "energy" of the recorded output was defined as:

$$x(A) = \frac{1}{T}\int_0^T v_A^2(t)dt \tag{6}$$

Here, the term "energy" is used in a signal processing context [24]. The energy in the usual physical meaning can be derived using the electrical load of the acquisition set-up, but that goes beyond the scope of this paper.

3. Experimental set-up

3.1. Materials and samples

Four test pieces were produced, each one obtained by piling up two concrete cubes measuring 10 cm on each side. Two kinds of discontinuities were obtained at the interface between the cubes. Two of the test pieces, which in the following will be denoted as specimens A1 and A2, were joined using a thin layer of cement paste. The two other test pieces, which in the following will be denoted as specimens B1 and B2, were laid one on the other, with cubes casting surfaces in direct contact. All cubes were produced using a concrete mix with CEM II A-L 42.5 R cement, ordinary aggregates (max. size = 16 mm) and a water to cement ratio equal to 0.74, with no admixtures. Their age at the date of testing was approximately six months.

The mechanical characteristics of the concrete were preliminarily evaluated by means of mono-axial static compression tests, that resulted in a compressive strength of 24 N/mm^2 (240 kN maximum load). The longitudinal wave speed in the cube was measured to be $v_t = 3850$ m/s and the density of the cubes was $\rho = 2330$ kg/m^3.

3.2. Testing equipment

The following ultrasonic testing equipment was used:

- Four identical piezoelectric transducers with a diameter of 40 mm and resonance frequency of 55.5 kHz. One was used as emitting source and the remaining three as receivers.
- An arbitrary waveform generator, used to drive the emitting source, forcing it to vibrate according to a burst law of 10 sinusoidal cycles at a frequency of 55.5 kHz. The amplitudes of the input signals thus generated were controlled in order to be progressively increasing.
- A high voltage linear amplifier.
- A data acquisition unit, equipped with an oscilloscope for real-time data visualization. Signals were recorded with a sampling rate of 10 MSa/s, according to Nyquist's theorem.

Linearity of the testing apparatus in working conditions was carefully verified in order to avoid any possible spurious effect that could alter the experimental data. Transducers were attached to the faces of each specimen through a thin layer of phenyl salicylate, whose linearity was preliminarily verified using a reference linear