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Conditioning and elastic nonlinearity in concrete: Separation of damping and phase contributions

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HIGHLIGHTS

- We study the nonlinear elastic properties of various concrete types and mortar samples.
- We analyze separately effects of nonlinearity on damping and velocities.
- We extend the Scaling Subtraction Method approach to analyze hysteresis effects.

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ABSTRACT

Elastic properties of concrete are affected, already at low strains, by its nonlinear properties, which are very sensitive to the presence of microcracks and hence to progression of damage. Conditioning and memory effects, which are both nonlinear effects are also manifested in intact samples and understanding their role in the definition of the propagation of elastic waves is crucial for the development of techniques aiming to quantify the nonlinear response and extract information about the microstructure of concrete specimens or concrete-based structures. Results are presented here to make evident the possibility to experimentally detecting and comparing the nonlinearity and conditioning induced by elastic modulus and damping nonlinearities in different concrete samples.

1. Introduction

Concrete exhibits a strong nonlinear hysteretic elastic behavior when excited by ultrasonic wave perturbations [1–5]. This behavior, which is common to other consolidated granular media [6,7], is strongly enhanced when the sample is damaged [8]. Quasi static loading [9,10], thermal stresses [11–13] or chemical damage (e.g. carbonation [14], corrosion [15], salts expansion [16] or alkali-silica-reaction [17–19]) are usually responsible of a significant enhancement of the nonlinear response, which can thus be used to quantify and characterise damage [8] and healing [20,21] of concrete samples and structures. Such enhancement of the hysteretic behavior is also observed in metals [22,23] and composites [24] when increasing the damage level.

Nonlinearity in the elastic response could be easily quantified, by considering the dependence on the excitation amplitude of the resonance frequency of the sample [19,25,26] or of the amplitude of higher order harmonics [27–30]. But also, break of the superposition principle [31,32], generation of subharmonics [33] or sidebands [34], nonlinear effects on coda [20,35] are indications of the hysteretic behavior. Furthermore, peculiar of this kind of non linearity is the conditioning/memory effect. After having been perturbed, the material linear elastic properties are different than those of the unperturbed material (in general softening is observed) [36–38]. The effect is fully reversible and slowly in time the material recovers its original properties [39]. Particularly interesting is the fact that the perturbing stress inducing conditioning could be a low stress, e.g. of the same order of magnitudes of the stresses induced by the propagating wave and exciting standard nonlinearity.

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From both theoretical and applicative points of view, it is of interest to separate contributions to nonlinearity and conditioning due to modulus and damping, which turns out into effects on velocity and phases [40] and amplitude [41], respectively. In particular, the relevance of the two contributions might be linked to the aggregates properties (e.g. size) and understanding such a link could be relevant for understanding the physical origin of the hysteretic elastic behavior in concrete and other building materials. Indeed, responsible of the peculiar elastic behavior observed could be different mechanisms, which in concrete are likely to be sliding between grains [42], static friction [43], clapping [44] or adhesion mechanisms linked to the nonlinear behavior in the water present at the interfaces between micro-cracks faces [45,46] (e.g. capillary forces).

The goal of this paper is to present a methodology suitable for separating contributions of modulus and damping to the hysteretic nonlinear response (including conditioning effects) of materials of interest in constructions. To achieve this goal, the chosen approach is based on the Scaling Subtraction Method – SSM [31,32], which allows separating in a direct way contributions of phases and amplitudes of the signal and could be an alternative to resonance frequency shift experiments [25] and other methods providing the measurement of an indicator which is mixing nonlinearity and conditioning and mixing phases and amplitudes effects. In view of distinguishing nonlinear elastic behaviors within samples with different characteristics and discriminate properties with a different quantitative behavior [47,48], we analyze here the hysteretic behavior of concrete samples with different grain/aggregates structures. Furthermore, we will extend the SSM approach to allow for quantification of small conditioning effects, which are normally neglected or unmeasurable with standard approaches.

In the next Section, the studied samples are analyzed, and the experimental set-up and procedures are introduced. In Section 3, results of our analysis will be presented and discussed. Finally, conclusions and perspectives are briefly outlined.

2. Experimental details

2.1. Samples

In order to discuss the proposed approach and show its validity in a variety of cases, we have considered a set of different samples with similar mechanical properties (high damping and similar wave velocities), but with different micro structure in terms of size of grains or aggregates (see Appendix A for more details about the samples). Although it was not possible to quantify explicitly the grain/aggregates sizes, still the differences between different classes of samples were easily detectable, ranging from "point like" grains (mortar and Berea) to several millimeter long aggregates (civil engineering concrete). The following specimens have been considered:

- Polymer concrete sample (intact): the sample was in the shape of a thin plate ($40 \times 11 \times 160\,\mathrm{mm}^3$). It consists of an epoxy resin matrix reinforced by sand and aggregates at 40%, 30%, and 30% volume fraction, respectively. Young modulus and Poisson ratio of the polymer concrete are evaluated as ≈ 30 GPa and ≈ 0.3, respectively (estimated from velocity measurements). Maximum aggregates size was less than 3 mm.
- Polymer concrete sample (damaged): same sample geometry and properties as for the intact polymer concrete sample, except that the sample contained micro cracks generated during a three point-bending fatigue test performed under 3 kN loading force, where the distance between the supporting pins was set at 120 mm. The experimental conditions create micro-cracks between the supporting pins with a main localization close to the center of the sample. Average microcracks length was smaller than 0.5 mm (see also details in Appendix A).
- Concrete used in civil engineering: it was available in the shape of a cylinder (4 cm diameter and 16 cm length). The sample was core-drilled from a casting prepared with 106 kg of cement (CEM II A-L 42.5 R), 436 kg of sand (0–5 mm), 312 kg of gravel (5–15 mm) and 68 kg of water (water-to-cement w/c ratio ≈ 0.6). The age of the cylinder at the time of testing was about 5 years, thus guaranteeing that the cement hydration process was completed. Curing of the original casting was completed in standard conditions. Three identical samples were tested with similar results. Here, results for sample A03 only are reported.
- Concrete used in civil engineering: in the same shape as the previous sample, but drilled from a casting differing slightly in composition: 340 kg of cement (CEM II A-L 42.5 R), 957 kg of sand (0–5 mm), 846 kg of gravel (5–15 mm) and 200 kg of water (w/c ratio ≈ 0.59). Age and curing of samples was the same as described above. Two identical samples were tested with similar results. Here, results for sample B06 only are reported.
- Mortar sample (P23): in the shape of a prism (3x3x14 cm^3). Mortar samples were produced using Portland cement (CEM I 42.5 N), with the use of sand aggregates (size less than 2 mm, with majority of aggregates with size smaller than 1 mm) and water (w/c of 0.3 by mass). The amount of aggregates in the mortar was about 42% by volume. The age of the prisms at the time of testing was about 5 years, thus guaranteeing that the cement hydration process was completed. Curing of the samples was done in water immersion (full saturation) for three weeks, followed by drying in ambient conditions (pressure, temperature and humidity) for additional three weeks.
- Berea sandstone sample: in the shape of a thin cylinder (1 cm diameter, 15 cm length). Grain sizes in the tested sample was of the order of tens of micrometers. Berea was considered in our study since it is a standard and well known material which exhibits hysteretic elastic properties.

2.2. Experimental set-up

The experiment was conducted generating ultrasonic signals through a waveform generator (Tektronix AFG 3022B). We have used here ultrasonic signals defined as monochromatic waves of amplitude A^{inp} and frequency ω_0:

$$u(t) = A^{inp} cos(\omega_0 t) \tag{1}$$

After amplification through a linear amplifier (CIPRIAN Model US-TXP-3, 200 x), signals were transmitted to an ultrasonic transducer (with broadband response up to a few hundreds of kHz) acting as emitter. The transducer was glued to the sample using Phenyl Salicylate (except in the case of the Berea sample in which plasticine was used). A second (identical) transducer was used to detect the response of the material under test and was connected to a digital oscilloscope (Lecroy 324A) for data acquisition. Signals were recorded in a short time window once stationary conditions were reached. In order to excite longitudinal modes (both transducers are working in compressional mode), the transducers were glued on opposite faces of the samples: the smaller lateral surfaces of the polymer concrete plate and the bases of cylinders and prisms (see also a schematic representation in Appendix B). In all cases the distance source-receiver was comparable and of the order of 14–16 cm.

Linearity of the acquisition system, including transducers and coupling, was verified in the frequency range up to 200 kHz and