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CONTRIBUTION OF ACOUSTIC EMISSION TO THE CHARACTERIZATION OF THE NONLINEAR BEHAVIOR OF COMPLEX MATERIALS

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ABSTRACT

The present work proposes an original experimental protocol to detect the nonlinear relaxation of concrete samples taken at intact and damaged states. This protocol is based on the passive monitoring of the nonlinear relaxation, which is usually performed using a low amplitude signal (probe) in slow dynamics experiments. Results show the relevance of the passive detection and reveal the existence of a 'silent period' during the first minutes of the nonlinear relaxation after which the AE hits start to be detected. The characteristics of the AE hits recorded during the passive relaxation showed a clear resemblance with those obtained during the damage of the different samples involving shear and compression mechanisms.

Keywords: *Slow dynamics - acoustic emission - complex materials - micro-cracking*

1. INTRODUCTION

Complex materials such as concrete (it could also be rocks, composites, or micro-cracked materials) have a particular mechanical behavior at the micro-scale level and are denoted as Nonlinear Mesoscopic Elastic Materials (NMEM). They exhibit a non-classical nonlinear behavior, which is characterized by the presence of hysteresis and memory effects in their stress-strain equation [1, 2, 3]. In the last decades, numerous studies have been developed to characterize the evolution of the microstructural changes (micro- cracks, contacts, etc.) within NMEM with the help of dynamic excitation. According to these studies, which are still relevant, hysteretic elastic nonlinearity is composed of two interlinked effects: the fast dynamics (FD) and the slow dynamics (SD) [4-6]. FD refers to instantaneous changes experimentally observed through harmonics generation, resonance frequency shift or dumping increase. The SD refers to the long-time dependence recovery of the elastic modulus and/or damping to its initial value (relaxation) after being softened by a large amplitude dynamic strain. The materials that exhibit FD and SD are characterized by soft regions within a small volume surrounded by hard regions. Despite the experiments and modeling developed in this field, the comprehension and experimental evidence of the physics, which lies behind the macroscopic observations are still needed. In order to advance knowledge around the micro-mechanisms involved in the nonlinear behavior of complex materials, this contribution proposes to follow the evolution of the nonlinear relaxation of micro-cracked concrete samples according to an original protocol. The latter is based on the listening of the acoustic activity during passive relaxation by means of calibrated piezoelectric sensors. [7]

2. EXPERIMENTAL SETUP

Nonlinear dynamic experiments are conducted on intact and micro-damaged samples by exciting materials at resonance

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around one of their bending modes. The applied standing wave dynamic method is also denoted as 'Nonlinear Resonant Ultrasound Spectroscopy' in some references [1-4]. Figure 1 depicts the experimental setup for the nonlinear dynamic experiments. A Stanford Research Systems SR785 analyzer is used to generate the excitation signal (linear sweep), which is amplified by a power amplifier (B&K type-2719) at a constant gain. The sample is firmly linked to the shaker (B&K type-4809) using a rigid clamping device. A piezoelectric sensor is glued on the other edge of the tested sample to detect its response. Vibration signals are first processed with the dynamic signal analyzer, which computed automatically amplitudes and phases for each frequency of the sweep source function around and away from bending modes. This analyzer is very stable for long-term measurements and its swept-sine excitation in terms of duration and signal-to-noise-ratio is ideal for the proposed resonance experiments. [8-10]

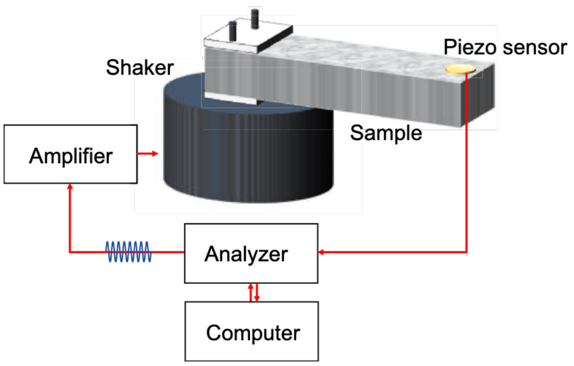

Figure 1. Schematic representation of the experimental setup used to perform the dynamic nonlinear measurements

3. NONLINEAR DYNAMICS OF POLYMER CONCRETE SAMPLES

Damaged Polymer Concrete (PC) sample was tested at a stress level corresponding to ~ 70% of its maximum strength using three-point bending tests. Nonlinear acoustic measurements are performed by exciting PC samples at intact and damaged states in fast dynamic (FD) and slow dynamic (SD) regimes. The results of both nonlinear dynamic excitations will be presented in the following.

3.1 Fast dynamics of polymer concrete samples

Fast dynamics (FD) experiments were conducted on PC samples having the same dimensions 200 × 40 × 40 mm^3. Samples were excited at intact and damaged states in the frequency range around the third bending resonance (between 5300Hz and 5450Hz). In the following, we denote A_{source} as the source amplitude of the linear sweep, f_0 as the linear resonance frequency and Q_0 as the linear quality factor, both obtained at the very low excitation. The amplitude of the excitation signal was gradually increased from 20 mV up to 2 V (before amplification) to excite the samples in the linear and nonlinear regimes. Note that the maximum excitation amplitude, i.e. A_{source} = 2 V, corresponds to a strain amplitude of ~ 6 × 10^{-6} at resonance.

Figurer 2 shows a results of PC sample which is excited around resonance at intact and damaged states. At the intact state, no strain amplitude-dependent phenomenon can be observed. This observation indicates that both resonance frequency and Q factor are not strain-dependent and the increase of the excitation does not influence the viscoelastic properties of the material, within the limits of the linear functioning of the experimental device. However, at the damaged state the resonance frequency (and Q factor not shown here) are considerably influenced by the increasing excitation amplitude A_{source}.

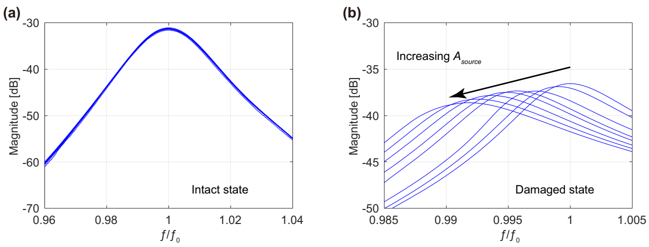

Figure 2. Evolution of the resonance bending mode during the fast dynamics (FD) of a PC sample taken at intact (a) and damaged (b) states.

3.2 Slow dynamics of polymer concrete samples

Slow dynamics (SD) experiments were performed on the same set of polymer concrete (PC) samples (intact and damaged). The experimental setup is identical to the FD, where the involved amplitudes belong to the linear operating range. The protocol of the SD experiment was considered in three steps, as shown in Figure 3.

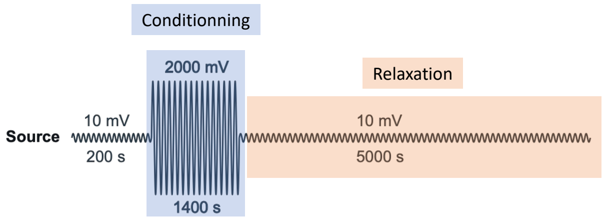

Figure 3. Protocol of excitation in slow dynamics experiment.

Figures 4 clearly shows the slow recovery of the elastic properties as a function of time in the case of the damaged PC sample, where the relaxation time is ~ 4200 s (monitoring during 5000 s). Results that were obtained by repeating the same resonance sweep, show that the tested sample has almost recovered its initial properties, where the variation of both resonance frequency and damping (not shown here) is less than 0.1%.

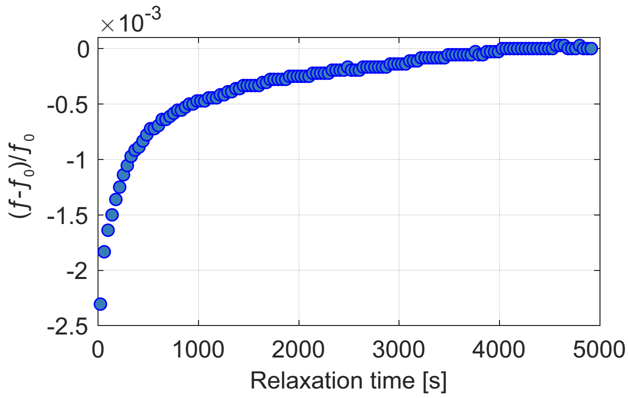

Figure 4. Relative variation of the resonance frequency as a function of time during the nonlinear relaxation of a polymer concrete sample taken at the damaged state.

The log-time evolution of the resonance frequency shown in Figure 4 show that during the first moments of relaxation, when the sample is probed using a low source amplitude, the tested sample is in a 'metastable state', which is similar to the observations performed in references [Mechri et al., 2019, Bentahar et al., 2020]. Indeed, in the middle time range, experimental results show that the recovery of elastic modulus and damping is linearly related to logarithmic relaxation time, in accordance with results of the literature [TenCate et al., 2000b, Bentahar et al., 2006, Scalerandi et al., 2010, Scalerandi et al., 2019]. This behavior has been observed for different media (consolidated and unconsolidated granular, damaged composites or metals, etc.), which is due to the hysteretic nonlinear relationship existing between stress and strain where different micro-structural features can be involved (sliding or frictional interfaces, clapping micro-cracks, etc.). Finally, we mention that the intact PC sample was not subject to relaxation, which makes the presence of recovery, in this case, a reliable acoustic signature of the presence and evolution of damage.

4. PASSIVE MONITORING OF THE NONLINEAR RELAXATION

By keeping the same experimental device previously used, intact and damaged samples were subjected to standing bending waves around their third resonance mode. In order to probe the relaxation and to get rid of the weak amplitude probe wave, an AE sensor was put on the sample to probe the relaxation as shown in the figure below.

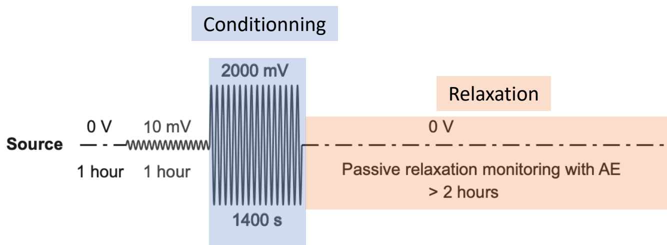

Figure 5. Protocol of the passive relaxation monitoring.

The long-time conditioning did not have any effect on the intact PC sample. Indeed, passive monitoring did not show the existence of any AE activity when the high voltage excitation is removed. This is due to the absence of slow dynamics, which has also been confirmed based on fast dynamic experiments during which the resonance curves remain unchanged in terms of frequency and damping for increasing excitation amplitude. During the relaxation of the damaged PC samples, we noticed the absence of AE activity during the early times of relaxation after the full conditioning (~ 600 s). Following this period qualified as a “period of silence”, we started to detect AE hits whose number was gradually increasing as a function of the relaxation time. The AE activity is plotted versus relaxation time in Figure 6. In the latter, each dot corresponds to an AE hit with a weak amplitude (between 30 and 34 dB, where 0dB ~ 1µV). The ‘silence period’ which seems to be a characteristic of the passive relaxation was around ~ 550 s for the presented data. The increase of damping during the conditioning period which was around 20% and the weak amplitude of the AE hits seem to be the main reason that prevents AE hits from reaching the surface of the sample with a measurable amplitude.

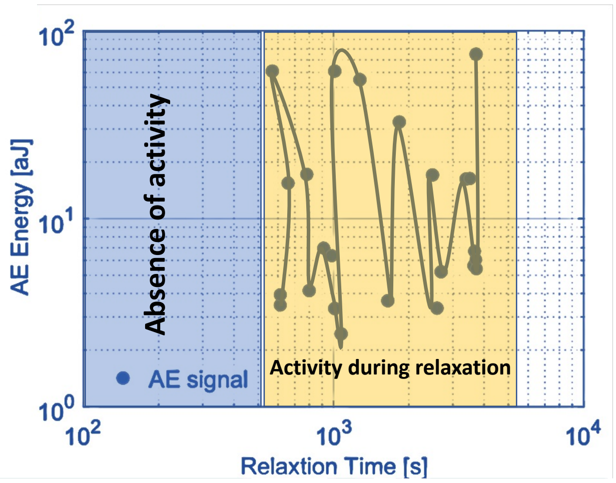

Figure 6. Acoustic emission activity during the passive relaxation monitoring.

Finally, the analysis of the AE hits recorded during relaxation has shown that they share the same characteristics with the AE hits recorded during the creation of the microcracks by means of a quasi-static three-point bending test. The resemblance can be observed for instance through the signals presented in Figure 7, where we can see that the acoustic signature related to the creation of microcracks within the matrix of the polymer concrete is present during the nonlinear relaxation.

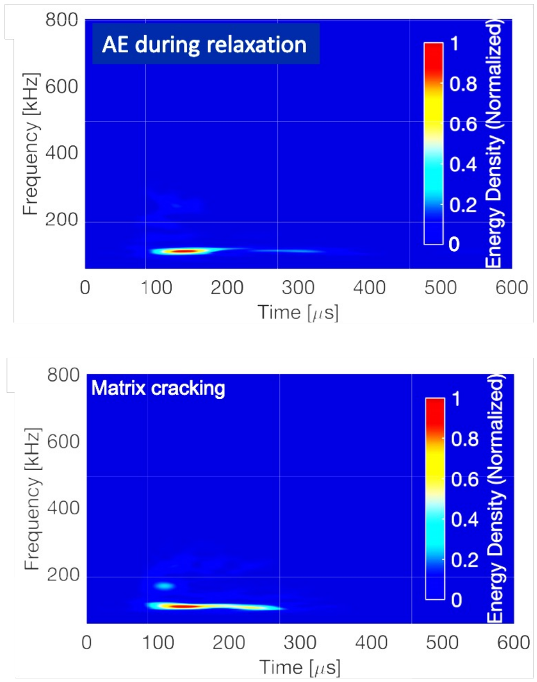

Figure 7. Time-frequency representations of AE hits detected during the nonlinear relaxation and during the quasi-static tests (matrix cracking).

5. CONCLUSION

This work proposed the use of a calibrated experimental setup which allowed to probe the evolution of the nonlinear dynamic behavior of concrete samples around resonance. Fast and slow nonlinear dynamic experiments were first performed using a weak excitation level. In order to get rid of the low amplitude probe signal, commonly used in slow dynamic experiments (active method), we proposed an original passive relaxation monitoring protocol based on the use of AE sensors. Results showed a very good sensitivity to relaxation using both active and passive methods. In addition, results showed the existence of a silent period where AE hits were not detected, which can be related to an important increase of damping during the nonlinear conditioning phase. Furthermore, the signal processing of the AE signals recorded during the passive relaxation showed a clear resemblance to those obtained during the quasi-static mechanical tests applied to the same concrete samples. As a perspective, a new study on the link between

AE hits and micro-mechanisms is being developed in the Laboratory of Acoustics of Le Mans University.

6. REFERENCES

[1] P. Johnson, P. Rasolofosaon : “Manifestation of nonlinear elasticity in rock: convincing evidence over large frequency and strain intervals from laboratory studies”, *Nonlinear processes in geophysics*, 3(2):77–88, 1996.

[2] K.V.D. Abeele, A. Sutin, J. Carmeliet, P.A. Johnson: “Micro-damage diagnostics using nonlinear elastic wave spectroscopy (news)”, *NDT & E International*, 34(4):239–248, 2001.

[3] G. Renaud, J. Rivière, S. Haupert, P. Laugier : “Anisotropy of dynamic acoustoelasticity in limestone, influence of conditioning, and comparison with nonlinear resonance spectroscopy”, *The Journal of the Acoustical Society of America*, 133(6): 3706–3718, 2013.

[4] M. Scalerandi, C. Mechri, M. Bentahar, A. Di Bella, A.S. Gliozzi, M. Tortello : “Role of slow dynamics in fast dynamics ultrasonic measurements“, *Comm. in Nonlinear Science and Numerical Simulation* 91, 105452, 2020.

[5] M. Bentahar, A. Di Bella, C. Mechri, S. Montresor, M. Scalerandi, X. Yu : “Exploiting slow dynamics effects for damage detection in concrete“, *Frontiers in Built Environment* 6, 64, 2020.

[6] M. Scalerandi, M. Bentahar, C. Mechri : “ Conditioning and elastic nonlinearity in concrete: Separation of damping and phase contributions”, *Construction and Building Materials*, 161, 208-220, 2018.

[7] X. Yu, M. Bentahar, C. Mechri, S. Montrésor : “Passive monitoring of nonlinear relaxation of cracked polymer concrete samples using acoustic emission”, *The Journal of the Acoustical Society of America*, 146(4), EL323-EL328, 2019.

[8] A. Novak, M. Bentahar, V. Tournat, R. El Guerjouma, L. Simon: “Nonlinear acoustic characterization of micro-damaged materials through higher harmonic resonance analysis”, *Non Destructive Testing & Evaluation International*, 45(1), 1-8, 2012.

[9] E-Y. Dris, R. Drai, M. Bentahar, D. Berkani : Adaptive Algorithm for Estimating and Tracking the Location of Multiple Impacts on a Plate-Like Structure“, *Research in Nondestructive Evaluation* 31 (1), 1-23, 2020.

[10] S. Toumi, C. Mechri, M. Bentahar, F. Boubenider, R. El Guerjouma : “Characterization of micro-cracking in polymer concrete using multiple scattered waves under steady-state vibration conditions“, *Research in Nondestructive Evaluation*, 28(1), 2017.