Non linear acoustic applied to the concrete study

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To characterize concrete, ultrasonic sound is a tool that has been developed to access damage and cracking. Its heterogeneity and the scales of sizes of micro-structural elements are necessary to consider a wide range of tools for characterization. We define the parameters that can be extracted from the wave propagation and vibration conditions into a beam in the laboratory. The scale measures are specified and the importance of each test condition is explained. We focus on nonlinear acoustics which is particularly appropriate for monitoring the developments on the mesoscopic scale. We study the conditions for harmonic generation and modulation, and specify the possibilities of working with energy. The beams in some cases are cracked over a determined length. The findings present the advantages of this technique and the difficulties inherent to their on site implementation.

1 Introduction

Civil Engineering structures are large-sized and control has to be developed over large areas or matter volumes. NDT implementation allows extending the tests while limiting the costs. Ultrasonic techniques hold an acknowledged position thanks to their sensitiveness to the evolutions of concrete, namely to its ability of resistance or its elasticity modulus. However a number of difficulties remain unsolved. They are linked to two aspects: the heterogeneity and the behaviour of the material. The former leads to a behaviour of the waves that is particularly difficult to model as far as the coherent part of the transmitted wave is concerned [1], [2]. The multiple diffusion, linked to the wave's interactions with the granulates notably, and the related lengthening of the distances, lead to a temporal distribution of energy over time. This particular behaviour has fuelled several studies in order to characterize of the material on the basis of the analysis of the incoherent part of the signal, called Coda [3], [4], [5]. Besides, concrete has a nonlinear behaviour due to its porosity and its diffuse network of microcracks as well as its intrinsic nonlinearity on the atomic scale.

This behaviour with a discrete and hysteretic memory has been studied in many cases like diffuse damaging by alkali reaction [6], thermal damaging [7], mechanical damaging [8], [9], [10]. Experimental and phenomenological approaches [11] allow, in some determined cases, to account for the behaviour or the evolutions of the material. The law of behaviour that characterizes the evolution of the elasticity modulus E_0 as a function of the strain ε and the classical β and δ coefficients as well as the hysteretic parameter of nonlinearity α.

$$\sigma = E_0\left[1 + \beta\varepsilon + \delta\varepsilon^2\right] + \alpha(\varepsilon, sign(\frac{d\varepsilon}{dt})) \qquad (1)$$

Another important issue is the characterization of microcracks in a civil engineering structure in order to predict the durability of the structure. The localization, the positioning and the depth of the cracks are key-elements to quantify the risks of rupture of a structure as well as the potential loss of tightness in the cases of an enclosure or a pipework under pressure. This is true for metal materials and structures made of concrete. In the case of metals some solutions are based on diffraction, wave attenuation as well as on the nonlinear behaviour of a crack.

A microcrack may be presented as being made of an opened part with a determined length that constitutes an obstacle to the wave propagation and that may generate a crossover frequency in the transmitted spectrum [12] or that may increase the flying time of the diffracted wave at the tip of the crack [13]. These techniques are exploited in certain industrial cases. However some difficulties clearly linked to a (part or complete) closure of the crack place this method at a disadvantage. This closure phenomenon is all the more true as we try to evaluate the state of microcracking under stresses.

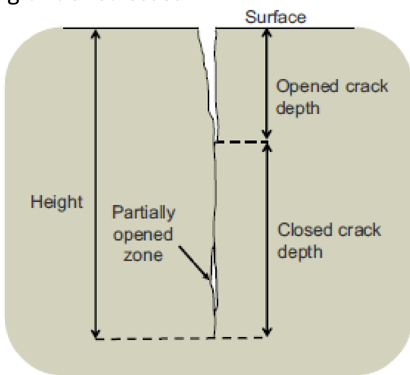

Figure 1 : Description d'une fissure
Figure 1 : Description of a crack

Figure 1 proposes the definition of the crack as composed of a part in which the edges are not in contact with (opened part) and of a part where contacts may exist in a more or less important quantity (closed part). Some nonlinear techniques based on the generation of harmonics have been observed experimentally in various materials with a linear behaviour such as glass, plexiglas or slightly nonlinear like steel or aluminium [14], [15], [16].

The work described in this article proposes two lines for studying the characterization of a microcrack. One is turned to the scale of the observation (be it global or local), and the other to the complementarity of the linear and nonlinear propagation approaches in front of the characterization of a crack in concrete. The crack is supposed to be partially closed.

2 Global approach

The measurements are based on an assemblage as described in figure 2. A concrete beam with a usual composition is placed on two supports. It may be stressed on the basis of a low frequency in alternate bending that favours the resonance of the beam and allows generating amplitudes of distortion high enough to show the nonlinear behaviour of the concrete. Measuring the displacements is carried out with the help of an accelerometer. In the case of global measurements, it alone records the displacement of the beam and allows determining the low frequencies of vibration.

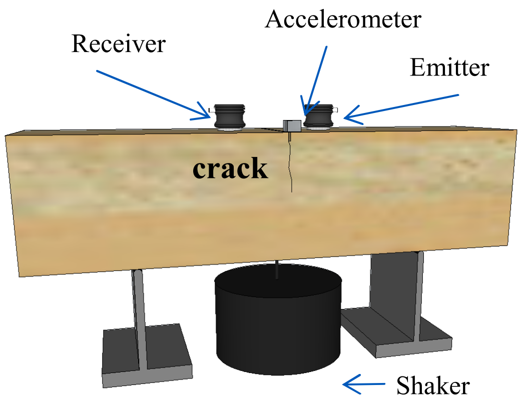

Figure 2 : Assemblage for testing on a concrete beam

In the cases of local measurements a set of two additional transducers allows furthermore generating and receiving a set of waves propagating through the sample and the crack.

The global measurements that we have developed consist in exerting some stress on the beam with high levels of distortion. The latter are sufficient to modify the actions of pressure and the localized behaviour of the material at the points of contact between the faces of the microcracks and possibly of those of the macrocracks. The problem to solve is to be in a position to separate the contributions of the micro- and macrocracks in the evaluations of the nonlinearity parameters of the concrete.

Several solutions are tested to evaluate these nonlinear parameters: the generation of harmonics [16] and the Nonlinear Resonant Ultrasonic Spectroscopy [17]. Both techniques are references in terms of measurement.

For the first case, a monochromatic wave f_1 is generated and the nonlinearity may be expressed by harmonics of the first order i, with an amplitude $A(if_1)$ proportional to that of the fundamental one A_1^i .
We can write [18]:

$$A(2f_1) \propto (\beta.(A(f_1)^2) \quad (2)$$

$$A(3f_1) \propto (\alpha.(A(f_1)^2) \quad (3)$$

This method has been exploited in the case of the damaging follow-up, but also in that of the presence of a crack in materials other than concrete.

For the second case, the NRUS technique allows quantifying the hysteretic parameter. Stressing a beam on its natural resonant frequency f_0 leads to losing some of the stiffness of the material with the increase in the distortion. The velocity then evolves and so does the frequency of resonance. This frequency discrepancy is proportional to the strain $\Delta\varepsilon$ generated in the beam by the ultrasonic wave. This amounts to writing :

$$\frac{\Delta f}{f_0} = \alpha.\Delta\varepsilon \quad (4)$$

Varying the amplitude of the solicitation then would be enough to increase the displacement of the beam step by step [19] in order to estimate the nonlinear hysteretic parameter α in the case of concrete.

In our case we have considered a set of four samples ($60*15*15$ cm^3) notched over 1 cm and cracked at various depths (0, 1, 3, 5.5 cm)

The objective of the tests is thus to follow the relative variations of the nonlinear parameter α extracted from each technique and according to the depth of the crack.

An example of the generation of harmonics for the I cm height cracked beam is displayed on figure 3.

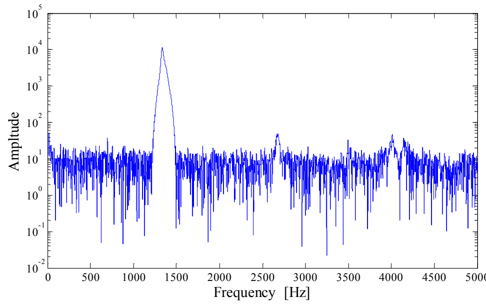

Figure 3 : Harmonic generation for a monochromatic wave frequency (f1= 1,400 Hz): 2.f1= 2,800 Hz and 3.f1= 4,200 Hz in the case of the 1cm crack depth beam.

An example of a resonance curve is proposed by figure4.

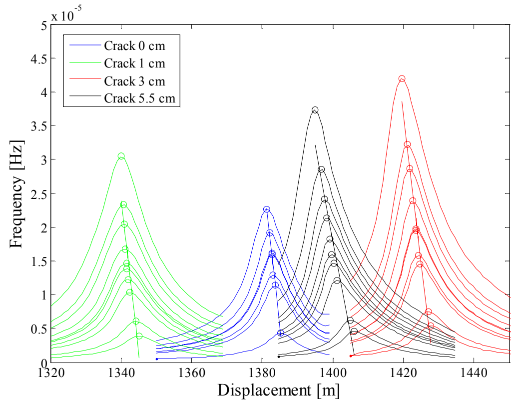

Figure 4 : Curve indicating frequency gap for NRUS cracked samples with various depths (0, 1, 3, 5.5 cm)

The results of the tests allow following the evolution of the nonlinearity parameters (arbitrary units) for a global approach, and according to the depth of the crack.

Figure 5 shows the absence of correlation in the amplitude of the harmonics with the depth of the notch.

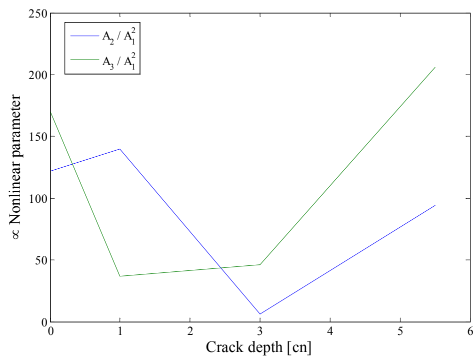

Figure 5 : Evolution of the nonlinear parameters α and β (arbitrary unit) with the depth of the crack

The increase in the size of the crack does not display a growth of the measured nonlinearity parameter.

Figure 6 shows the evolution of the resonance frequency gap normalized with the crack depth. In this case, only the sample with an important crack depth (5.5 cm) shows a behaviour different from that of the other samples with smaller-sized cracks. As the crack represents about 40% of the height of the sample, the contributions of the crack's nonlinearity are becoming more and more important and are distinguishable from those of the sample.

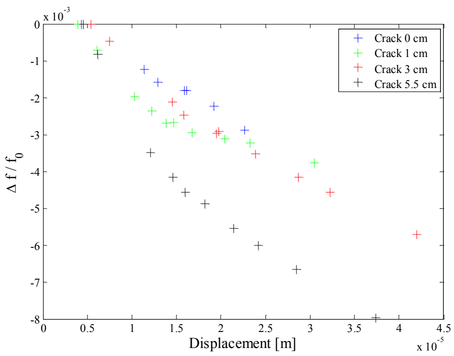

Figure 6 : Evolution of the resonance frequency gap with the displacement amplitude.

For the three smaller crack sizes, the coefficient of proportionality to α remains noticeably constant.

As a conclusion, the global measures of the study of the nonlinear behaviour of the cracked samples make it only possible to dissociate the larger macrocracks from the intrinsically nonlinear behaviour of the concrete material. The measured nonlinearity is essentially related to that of the porosity and diffuse microcracking network that is globally stressed. However it is still possible to detect a macrocrack with this approach under some conditions of its having a minimum size.

3 Local approach

As the global approach does not allow extracting all the pieces of information useful for the in-depth sizing up of a macrocrack, we have developed the other line of auscultation that is related to a localized analysis of the behaviour. It is based on an auscultation close to the crack by a wave transiting in the sample by ways passing through the crack.

Here again two methods have been implemented.

The first consists in analyzing the incoherent linear part of the waves, particularly the space-and-time distribution of energy in the received signal. The approach is a static one. The sample is not subjected to a bending stress, the couple of transducers alone (positioned on both sides of the crack) emit then receive the signal (with a bandwidth centered on 500 kHz) that has been diffused in the whole of the sample and transits several times through the macrocrack. An approximation of the scattering regime of diffusion by the radiation equations displays the space-and-time variations of the spatial density of energy in the received signal $\langle E(x,t,f)\rangle$ as compared to that of the source $P(x,t,f)$.

$$\frac{\partial\langle E(x,t,f)\rangle}{\partial t} - D\Delta\langle E(x,t,f)\rangle + \sigma\langle E(x,t,f)\rangle = P(x,t,f) \qquad (5)$$

With x being the position, t the time, f the frequency, D the diffusivity, σ the dissipation. Diffusivity ($m^2\ s^{-1}$) is a characteristic of the microstructure (density, geometry and distribution of the aggregates). Dissipation (s^{-1}) is linked to the viscoelastic properties of the medium and more essentially to that of concrete paste [20].

Several authors [21] and [22] have tried to evaluate the diffuse part of the energy on the basis of this principle in the case of samples made of notched, but not cracked concrete. The variation of energy as a function of the time of the received signal is realized with a window for sliding temporal analysis.

The smoothing of the energy by the function (5) allows evaluating the parameters D, σ and $ATME$ (Arrival Time of the Maximum Energy) as shown in figure 7.

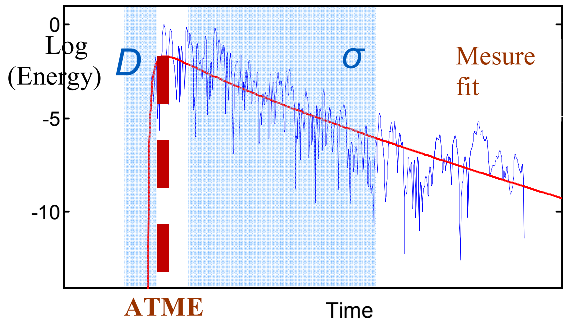

Figure 7 : Smoothing (unbroken line) of the evolution of the energy transported by the signal as a function of the time by a 2D solution [21] of equation (5)

Our tests and exploitations carried out on this principle are detailed in another work? [23].

The results proposed in figure 8 compare our macrocracked samples presenting different crack depths (blue) with another series made of the same material, but only notched and not cracked, and for different notch depths (red).

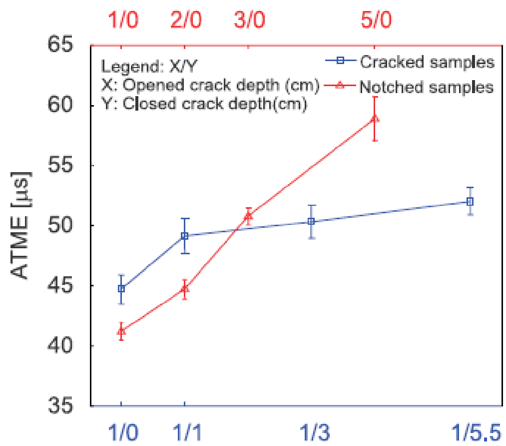

Figure 8 : Evolution of the ATME with the notch depth (red) or the crack depth (blue)

It then becomes possible to compare the sensitiveness of the aforementioned parameters to the presence and depth of cracks called opened cracks represented by the notches, or partially closed represented by the cracked samples.

Among the three parameters, the ATME alone is in a position to bring information on the state of the crack with a limited uncertainty. This parameter is sensitive to the evolution of the notch depth (red) and not to that of the crack depth (blue). It then becomes possible after calibration to bring out the opening depth of a detected crack.

The second local method consists to stress the beam by means of an impact. The first mode of resonance ($f_1 = 1{,}5kHz$). Simultaneously the auscultation of the zone close to the crack is carried out by two transducers at a frequency $f_2 = 49kHz$. The modulation of the high frequency generates a signal composed of components modulated at $f_2 \pm f_1$.

In the case of an exploitation in the frequential space, the nonlinear parameter α is extracted from the ratio between the energy generated in the lateral side bands E_{SB} close to f_2 (including the modulated components) and the energy of the signals brought by the high E_{HF} and low E_{BF} frequencies [24]

$$\alpha \propto \frac{E_{SB}}{E_{HF}.E_{BF}} \tag{6}$$

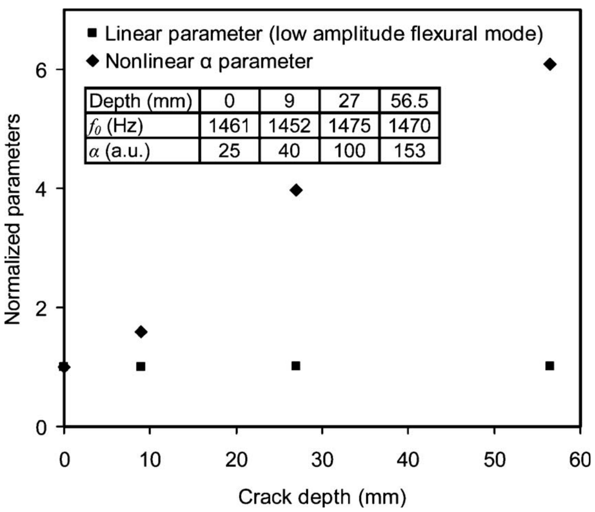

Figure 9 : Evolution of the nonlinear (arbitrary unit) and linear parameters with the depth of the crack

The results of our test and exploitation conditions, presented in another work [25], show, in figure 9, an important dependence of the linear parameter on the depth of the crack. The extremely slight evolution of the linear parameter as defined by the resonance frequency in flexion mode 1 of the sample is presented as a comparison. The uncertainty of the evaluation of the non linear parameter measured on one of the samples is 23%.

4 Conclusion

This work has allowed comparing the global and local approaches to detect and size up cracks with different sizes.

The tests carried out in laboratory conditions show that the global measurements are not enough to obtain all the information for detecting and sizing up a crack. Only the resonance (NRUS) leads to this information. It makes it possible to detect a crack without being in a position to extract out of it a piece of information that could help determining the depth. In the cases of in situ tests, it would require the exertion of an alternative stress with a variable amplitude on the wall of the structure as well as the displacement of the accelerometer in order to measure the variation of the proportionality coefficient between the resonance gap and the amplitude of the stress. This technique requires identifying the working) frequency.

The tests carried out within the frame of the local approach allow extracting information on the sizes of the cracks. The linear parameter ATME in particular must lead to the evaluation of the depth of the so-called opened crack whereas the nonlinear parameter obtained by frequency modulation must lead to the evaluation of the closed part of the crack.

These two approaches may be complementary with the implementation of the global evaluation to detect a crack, even a non emergent one, then that of the local evaluation to size it up in terms of opened and closed depth of the crack. An instrumentation without contact has to be envisaged in order to improve the repeatability and to reduce the measurement time.

Acknowledgments

The authors thank EDF for its support during this work.

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