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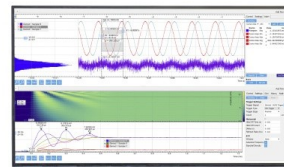
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Monitoring Localized Cracks on Under Pressure Concrete Nuclear Containment Wall Using Linear and Nonlinear Ultrasonic Coda Wave Interferometry

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Abstract. Civil engineering is constantly demanding new methods for evaluation and non-destructive testing (NDT), particularly to prevent and monitor serious damage to concrete structures. In this work, experimental results are presented on the detection and characterization of cracks using nonlinear modulation of coda waves interferometry (NCWI) [1]. This method consists in mixing high-amplitude low-frequency acoustic waves with multi-scattered probe waves (coda) and analyzing their effects by interferometry. Unlike the classic method of coda analysis (CWI), the NCWI does not require the recording of a coda as a reference before damage to the structure. In the framework of the PIA-ENDE project, a 1/3 model of a prestrained concrete containment (EDF VeRCoRs mock-up) is placed under pressure to study the leakage of the structure. During this evaluation protocol, specific areas are monitored by the NCWI (during 5 days, which correspond to the protocol of nuclear power plant pressurization under maintenance test). The acoustic nonlinear response due to the high amplitude of the acoustic modulation gives pertinent information about the elastic and dissipative nonlinearities of the concrete. Its effective level is evaluated by two nonlinear observables extracted from the interferometry. The increase of nonlinearities is in agreement with the creation of a crack with a network of microcracks located at its base; however, a change in the dynamics of the evolution of the nonlinearities may indicate the opening of a through crack. In addition, as during the experimental campaign, reference codas have been recorded. We used CWI to follow the stress evolution and the gas leaks ratio of the structure. Both CWI and NCWI results are presented in this paper.

INTRODUCTION

The state of health of reinforced concrete structures is a particularly important issue in the field of nuclear safety (nuclear containment wall, waste storage drums). In this particular area, checking the tightness is one of the main motivations. The loss of sealing is mainly due to the presence of open cracks. The knowledge, the location and finally the characterization of these cracks is then an important factor in the qualification of the damage state of the structure. Several techniques exist to evaluate and characterize concrete damage [2], but their sensitivities can sometimes be insufficient with regard to the size of the cracks. On the other hand, other techniques can be used with great sensitivity but their implantation remains difficult (RX, MRI). The technique of interferometry of the ultrasonic coda (Coda Wave Interferometry or CWI [3,4]) is a good candidate for the evaluation of small changes in the structures of complex material such as the concretes [5]. This technique based on the generation and propagation of multi-scattered ultrasonic waves makes it possible to detect the appearance of cracks. The interferometry is performed by the stretching method [4]. This consists in calculating the correlation coefficient CC between a reference coda dilated or compressed temporally and a coda in a perturbed state such as:

$$CC(\theta) = \frac{\int_t^{t_2} u_r[t(1+\theta)]u_p[t] dt}{\sqrt{\int_t^{t_2} u_r^2[t(1+\theta)] dt} \sqrt{\int_t^{t_2} u_p^2[t] dt}}$$

where u_i and u_p are, respectively, the reference coda and the coda in a perturbed state, θ the coefficient of expansion/compression of the reference signal, t_1 and t_2 are the start and the end of the calculation window of the correlation coefficient. By maximizing the correlation coefficient for a series of expansion coefficients, two observables are extracted:

- θ corresponding to the velocity variation of the coda waves ($\theta = dv/v$),
- Kd corresponding to the de-correlation between the two windowed signals, $Kd = 1 - CC(\theta)$.

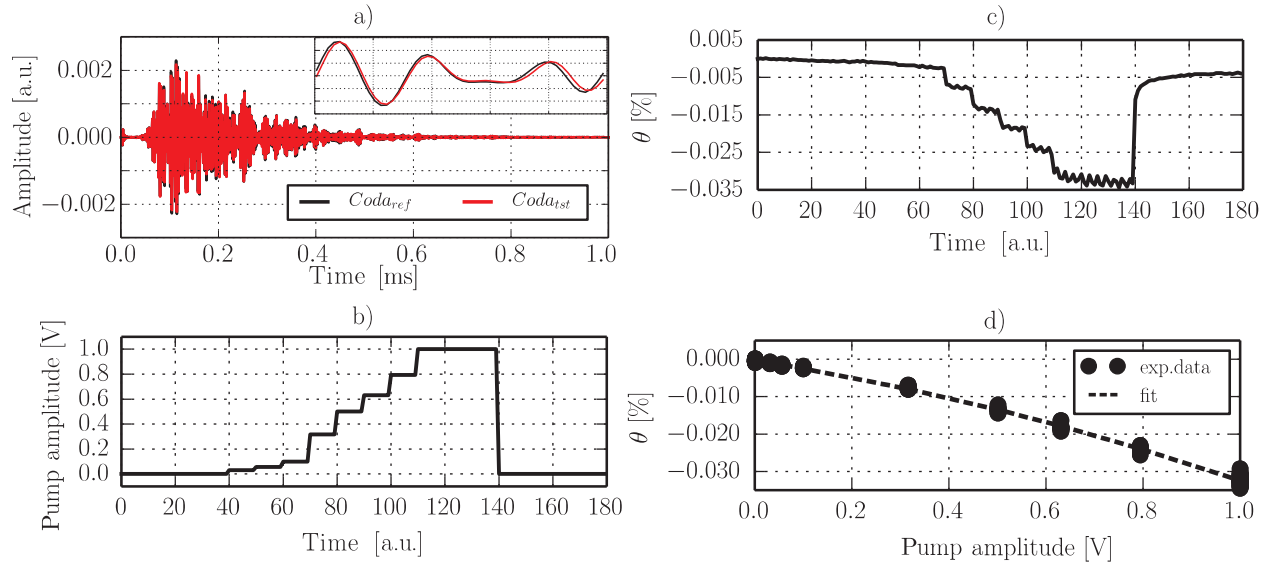


FIGURE 1. a) Illustration of coda waves. In black, the reference coda. In red, a coda recorded at a disturbed state. The two coda seem to be identical but a zoom (in inset) over a few periods at $t = 0.25\text{ms}$ makes it possible to visualize the very small difference in phase and in amplitude. b) The change in acoustic pump amplitude. c) Evolution of the variation of velocity θ during the NCWI protocol. d) Evolution of θ as a function of the amplitude of the pump. The nonlinear observable α_θ corresponds to the slope of this variation. The same process is performed to extract α_{Kd} .

However, due to the relative nature of the method, the acquisition of a reference signal (u_i) during a healthy state of the material is required. To overcome this difficulty, a new method of nonlinear acoustics based on the coda mixed with low frequency and high amplitude waves was developed in collaboration with Ifsttar/Laum [6, 7, 1, 8, 9]. Initially proposed by [10] the nonlinear modulation technique has been applied to the coda [6, 7]. The protocol of this measurement consists in successively increasing the amplitude of the pump (Fig. 1 b) and in measuring for each amplitude the variation of speed by the stretching method. If the material has a nonlinear character (by its nature or in the presence of a defect), then the variation in velocity between two states with and without a pump is non-zero (Fig. 1 c).). Two observables characterizing the nonlinearities α_θ and α_{Kd} are then extracted by regression (linear or quadratic) of the dependence of the variation of velocity and the de-correlation as a function of the amplitude of the pump (Fig. 1 d).). The main advantage of this nonlinear technique is that it is no longer necessary to have a coda in a healthy state. The reference for stretching is taken when the pump level is zero. The sensitivity of this method makes it possible to detect and characterize micro-cracks in concrete [7]. It is also possible to follow the evolution of micro-cracks in structures as in the case of self-healing in concretes by following the variation of the nonlinearities α_θ and α_{Kd} [1]. It should be added that this technique is particularly suited to measurements in real structures. Not knowing the healthy state but knowing the order of magnitude of the nonlinearities of the material in a healthy state allows a prognosis for the presence of microcracks to be given at any time [11].

EXPERIMENTAL SETUP AND PROTOCOL

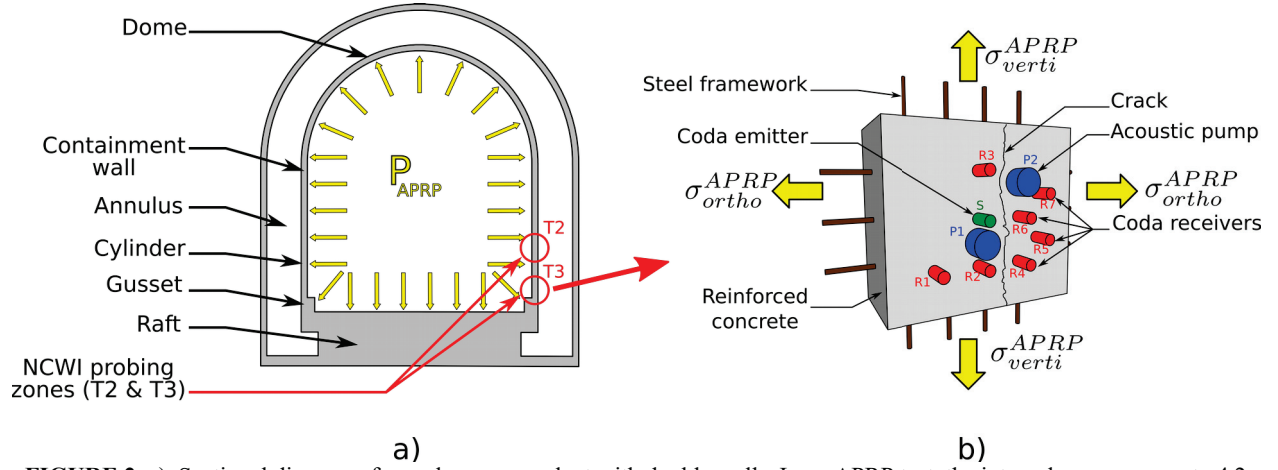


FIGURE 2. a). Sectional diagram of a nuclear power plant with double walls. In an APRP test, the internal pressure rose to 4.2 bar (relative). The NCWI monitoring area is located near the raft/gusset junction. b) Measuring device by NCWI. The coda are generated by the source “S” and then recorded by the sensors “R1” to “R7”. Simultaneously, acoustic pumps “P1” and “P2” generate low-frequency waves to create a nonlinear perturbation. The increase of the pressure inside the confinement enclosure generates tensile stresses on the probed zone.

As part of nuclear safety research, containment walls of nuclear power plants are put under pressure every ten years in order to measure their tightness. This pressurization, called APRP (French acronym for Loss in Primary Coolant Accident), consists of inflating the enclosure to a pressure of 5.2 bar (4.2 bar relative) and then measuring the amount of air lost by leakage (Fig. 2a). In the framework of the PIA-ENDE project, a 1/3 model of a prestrained concrete confinement enclosure (VeRCoRs for Realistic Verification of Reactors Containment) was built on the French EDF Lab Les Renardières site, in order to study the health state of concrete using several recently developed non-destructive testing (NDT) techniques. The APRP test protocol consists of increasing the pressure gradually up to 4.2 bar (relative) for a period of 24 hours (Fig. 3 a.) During the first tests, several open cracks were observed and listed. The monitoring zone by NCWI is then positioned on a vertical crack in order to follow its evolution during the test. During this period, the NCWI probing is conducted every 30 minutes. The device is shown in Fig. 2 b). The principle is as follows:

1. A sinusoidal chirp with frequency from 200 to 600 kHz is generated by a piezoelectric source (“S” in green on Fig. 2b),
2. The nonlinear regime is realized by two acoustic pumps which generate a sinusoidal chirp from 10 to 50 kHz (P1 and P2 in blue on the Fig. 2b),
3. Finally, the coda are recorded by seven ultrasonic sensors (R1–R7 in red on Fig. 2b).

The two nonlinear observables α_θ and α_{Kd} are then extracted by quadratic regression of the variation of # and Kd as a function of acoustic pump amplitude U_{pump} :

$$\theta(U_{pump}) \propto \alpha_\theta U_{pump}^2$$

and

$$Kd(U_{pump}) \propto \alpha_{Kd} U_{pump}^2.$$

The aim of this work is to follow the evolution of these two observables as a function of the pressure measured inside the confinement enclosure.

RESULTS

The evolution of the CWI observables during the APRP test are presented on Fig. 3b) and c). All the sensors on both probed zones show a clear trend as the pressure (Fig. 3a) inside the containment increase. The variation of velocity θ decreases as the internal pressure increases, but the dynamic is different for the two zones. Indeed, the healthy zone increases more than the cracked zone. This is due to the fact that the cracked zone is located near the raft/gusset and where the strain is lower than the healthy zone located higher on the structure. The de-correlation Kd does not show a clear difference between the two zones. However, on both CWI observables, the leakage of the structure is visible between 10 and 15 hours. The evolution of the nonlinearities α_θ and α_{Kd} during the test is presented in the Fig. 3d) and e). The evolution of α_θ shows a clear trend of the increasing in elastic nonlinearity. Both healthy and cracked zones have quite the same slope as the internal pressure increases; however, the offset in nonlinear elasticity is higher in the cracked case. The evolution of α_{Kd} is more interesting: the higher the pressure, the greater the nonlinearity. Indeed, the internal pressure generates a negative stress which increases the number of weak contacts in the emerging crack. Moreover, this negative stress favors the opening of the microcracks at the paste/aggregate interfaces. Indeed, the micro-contacts of the solid bridges in the crack generate strong nonlinearities in particular by a phenomenon of clapping.

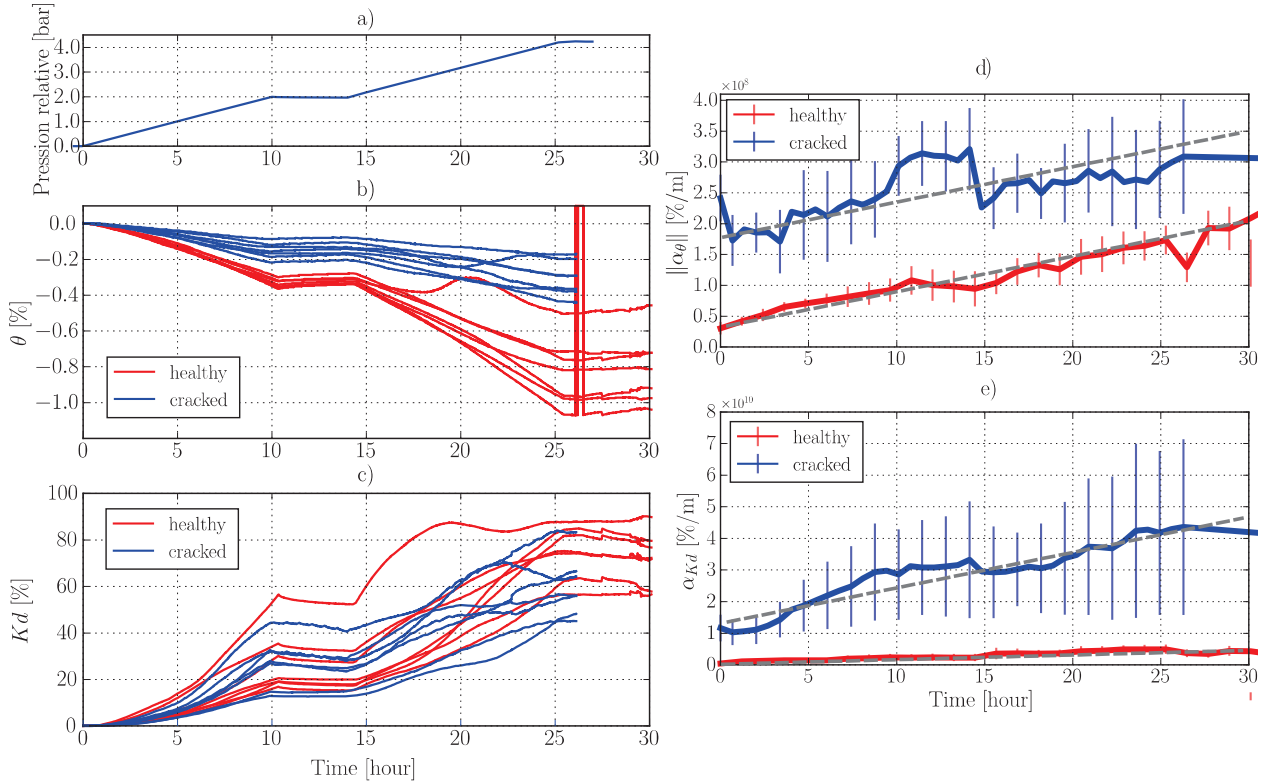


FIGURE 3. Evolution of CWI and NCWI observables during an APRP test: a), the pressure changes inside the containment; b) and c), respectively, the evolution of θ and Kd during the test for all the sensors on the healthy zone in red and the cracked zone in blue; d) and e), respectively, the evolution of the averaged nonlinearities α_θ and α_{Kd} during the test on the healthy zone in red and the cracked zone in blue.

CONCLUSIONS

In this work, the evolution of acoustic nonlinearities is monitored during a pressurization test of a nuclear reactor confinement enclosure. As the pressure increases, the ortho-radial and vertical stresses lead to crack opening, which leads to an increase in nonlinearities. At present, the opening width of the crack can only be determined with nonlinear observables. On the other hand, a non-proportional variation of the dissipative nonlinearity as a function of the internal pressure indicates that a crack is created near the sensors recording this change of dynamics.

ACKNOWLEDGMENTS

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