Non-destructive Evaluation of Concrete Damages of Containment Walls in Nuclear Power Plants

Mehdi Sbartaï[1], Vincent Garnier[2], Cédric PAYAN[2], Bogdan Piwakowski[3], E. Larose[4], J. Saliba[1], N. Ranaivomanana [5], Jean-Paul Balayssac [5]

[1] I2M Laboratory, GCE Department, Univ. Bordeaux, 351 cours de la Libération, 33405 Talence, France, email: zoubir-mehdi.sbartai@u-bordeaux.fr

[2] Aix Marseille University, Laboratory of Mechanics and Acoustics, LMA CNRS UPR 7051, 31 chemin Joseph-Aiguier 13402 Marseille CEDEX 20, France

[3] IEMN École Centrale de Lille, 59651 Villeneuve d'Ascq Cedex, France

[4] ISTERRE – UMR 5275, 38 041 Grenoble, France

[5]LMDC, INSA/UPS Génie Civil, 135 Avenue de Rangueil, 31077 Toulouse cedex 04 France, email

ABSTRACT. *This paper is focused on the part of the project ANR ENDE that concerns the damage and crack characterization by means of NDT. The tests are done in 3 or 4 points bending in order to study the cracks' generation, their propagation, as well as their opening and closing. The main ultrasonic techniques developed concern linear or non-linear acoustic: acoustic emission [SBA 2015], Locadiff [LAR 2015], energy diffusion, surface wave's velocity and attenuation, DAET [3]. The recorded data contribute to providing the mapping of the investigated parameters, either in volume, in surface or globally. Digital image correlation is an important additional asset to validate the coherence of the NDT results.*

RÉSUMÉ. *Il est nécessaire d'utiliser les méthodes non-destructives pour une bonne évaluation des structures en béton et notamment les ouvrages sensibles comme les centrales nucléaires. Dans le cadre du projet ANR ENDE, plusieurs développements ont été effectués en méthodes non destructives. Cet article présente les résultats d'une large campagne expérimentale qui a pour objectif de qualifier des méthodes END nouvelles pour la détection de l'endommagement diffus et la détection et la caractérisation des fissures (position, longueur, etc.).*

KEY WORDS: *NDT; damages; detection; acoustic; coda.*

MOTS-CLÉS : *END, endommagement, détection, acoustique, coda.*

1. Introduction

The containment structure is one of the substantial protective barriers in a nuclear power plant. It must support external solicitations, as in the case of strong mechanical one. It must also ensure leak tightness in case of internal overpressure, as associated with a reference accident corresponding to a primary circuit failure. Both functions, which must be fulfilled anytime, are highly dependent on the state of the concrete. Monitoring the concrete ageing and damage is thus a constraint affecting not only the safety but also the decision-making with regard to the potential plant lifetime extension.

In the ENDE National project 'Non-destructive testing of the containment structures of nuclear plants', we test the use of Non-Destructive Testing (NDT) as an alternative to destructive testing, which is prohibited inside NPPs, to evaluate the properties of the concrete and to propose new approach to detect the local damage and cracks. This project is part of the "Nuclear Safety and Radiation Protection Research" French program which clearly raises the issue of the safety of nuclear plants.

The characterization of the damage state and the cracking is done by means of several NDT from which it is possible to assess the cracks depth and opening. Some authors have worked on the cracks detection. They often use ultrasonic waves propagation to detect or map a crack or/and a damaged zone. The impact echo is associated with a stack imaging of spectral amplitudes procedure to map voids or delamination [MAT 2010]. It is associated with Radar but without combining the two sets of data. In the case of cracks perpendicular to the surface, the vibration analysis based on the baseline updating method allows to localize the cracks and to follow their propagation [BUD 2005]. Surface waves generated by pencil lead break are also exploited to follow the growth of a crack in concrete [AGG 2011]. These authors have shown that the scatter and the central frequency depend on the crack depth. The complementarity of techniques is studied to follow the propagation of a crack in a bending test [WOL 2015]. Acoustic Emission, Digital Image Correlation are associated to the propagation and attenuation of ultrasonic waves measured with embedded sensors. A new technique Locadiff allows locating the modification generated by the early stage of cracking by measuring the spatiotemporal de-correlation of scattered waves and by solving the corresponding inverse problem. This technique was applied on a real–size concrete specimen and on a four-point bending test specimen [LAR 2015] to map the mechanical changes, fracture opening, and damage development.

The objective of this paper is to propose a methodology as well as non-destructive techniques to characterize the containment structure concrete and sealing specifically for nuclear power plants. In this paper, we present the research work concerning the determination of the damage. We focus on the laboratory investigation of concrete specimens tested in 3 points bending. The aims are to identify the generation of the diffused damage in the zone of maximum stresses and during the increase of the load to follow its development and after its transformation into a crack.

2. Materials and methods

The goal of the experimental tests is to follow the different steps of crack generation and propagation, from the development of diffuse damage to the generation of a crack and its propagation. The generation of cracks, as well as their influence on the leakage rate, is also examined.

Follow-up testing of diffuse damage and its transition to continuous damage as well as that of interface cracks is carried out on 50x25x12 cm3 specimens (Fig. 1a).

The NDT techniques implemented are: surface waves, diffuse waves, localization and diffusion, time reversal, acoustic emission, digital image correlation. WP3 laboratory tests and results will be developed in this paper. Specific tests will identify the link between NDT measures and the leaks in the concrete or at the aggregate matrix interfaces. Spatial data from the different NDT measurements are restructured by using a single mesh size of $1cm^3$.

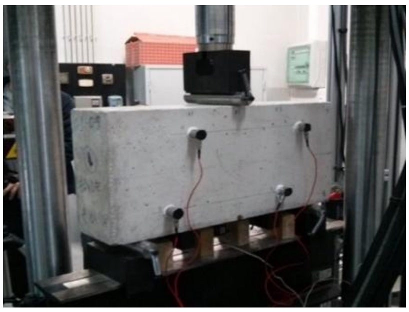

Figure 1. *Three points bending test.*

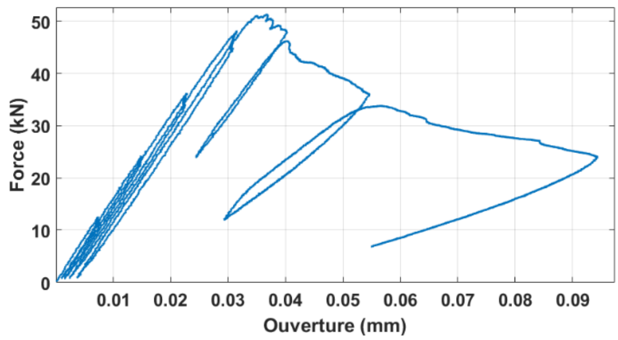

Figure 2. *Force-CMOD curve.*

3. Results and discussion

The Surface Waves technique is developed with automated devices [ABR2012, KAC2016]. The one used to follow the cracks was the automated scanner shown in (Fig. 3a). It works with two ultrasonic air transducers (Fig. 3b). The emitter sends a wave that propagates through the surface concrete on a depth close to the wave length. The receiver moves along the surface to record the signal. The device was operated on the lateral face of the sample that has been auscultated on a line perpendicular to the cracks. The surface wave attenuation A(X) has increased roughly when the cracks crossed the path of the waves (Fig. 3c).

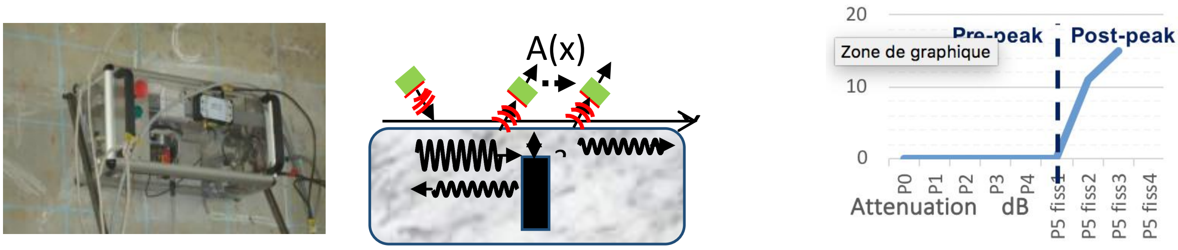

Figure 3. *a) Ultrasonic surface waves scanner, b) Principle, c) Attenuation of the surface wave.*

The Diffused Waves technique [QUI 2012] analyzes the wave energy transportation through the sample with a crack (Fig. 4a). One of the Non-Destructive Parameters used is the Arrival Time of the Maximum of the Energy (ATME) shown in Fig. 4b by the blue point. We can follow the increase of the crack depth through a simple model as presented in (Fig. 4c).

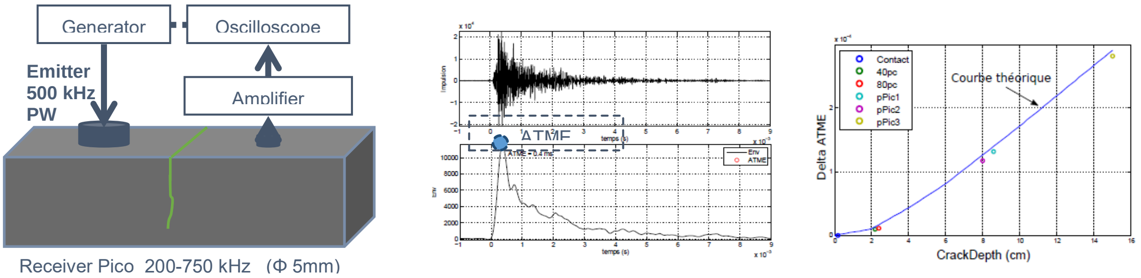

Figure 4. *a) Diffused Waves analysis b) ATME c) Link between ATME and the crack depth*

The Locadiff technique [LAR 2015] uses the evolution of the diffused waves obtained from a transducers network (Fig. 5a: 10 emitters, 10 receivers). A small perturbation in a material with multiple scattering is identified. This technique allows evaluating the strain state of the sample by the relative variation of velocity and estimating the damage and the crack by decorrelation of the wave forms. The results show the strain (Fig. 5b) and the crack length (Fig. 5c). The size of the voxels is 2x2x2 cm^3.

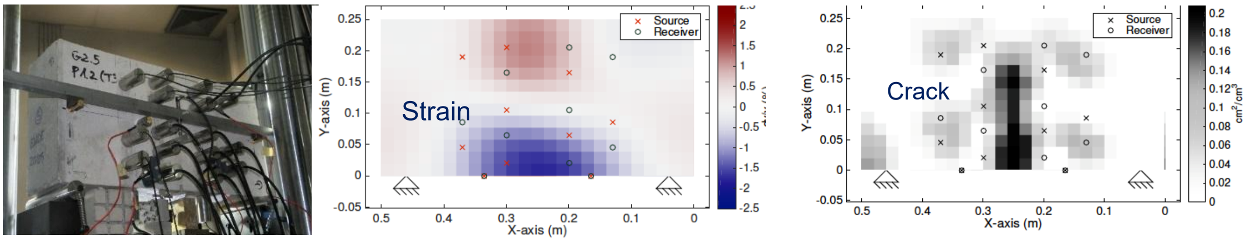

Figure 5. *a) Transducers distribution b) Strain before the peak c) Crack propagation after the peak.*

The Digital Image Correlation (DIC) works with the displacement measurement of the points of a speckle pattern (Fig. 6a), [TAH 2010]. It allows evaluating the strain state of the sample (Fig. 6a) and also by the way, the length (Fig. 6c) and the opening of the crack. From a theoretical point of view, the crack opening corresponds to the displacement jump between two points located from either side of the future crack path. This holds particularly in the case of a visible and wide-opened macro crack (more than a few micrometers).

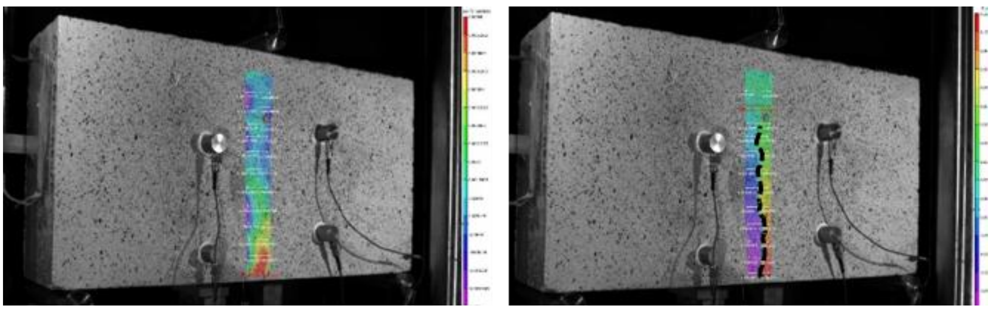

Figure 6. *a) Stain distribution, b) Crack way and opening*

The Acoustic Emission [SBA 2015] is a passive technique that allows following all the events that occurs in the sample with 8 receivers (transducers frequency of 150 kHz). These events correspond to the generation of micro cracks of damage or to the propagation of the crack(s). The events are recorded by the transducers and counted following a cumulative or instantaneous process. Each event, under conditions, is positioned by using the information from all the transducers (Fig. 1a). The results of a continuous auscultation of one of the samples can give us the density of the damage (Fig. 7a) and or the density of the energy close to the crack (Fig. 7b). The length of the crack is also extracted based on the events density distribution. A comparison between AE results and DIC show good correlation (Fig. 7c).

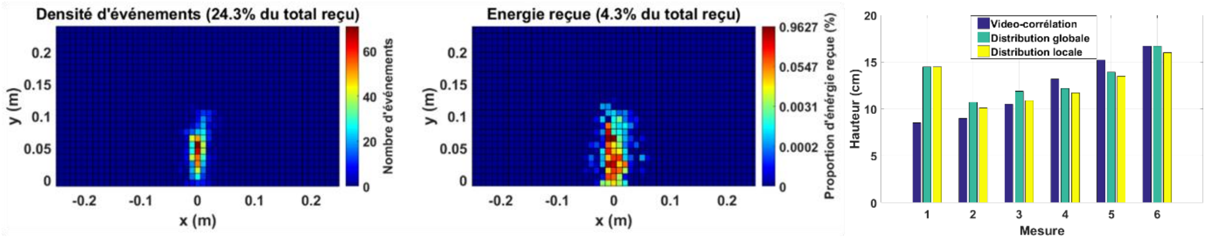

Figure 7. *Density distribution (a) and energy (c) of EA events, (c) comparison of crack length measurement with EA and DIC.*

4. Conclusions

The NDT applied on samples under 3 points bending tests allow to follow up of the damage and crack. We classified the techniques in 3 levels. The results were obtained for each level. The bulk techniques are merged and compared with DIC reference results. The results are in very good agreement. The next steps are to sample the bulk techniques with the DIC results and to implement this test and data fusion process for on-site measurement. The first has already been done. The data are just under treatment processing. Next, all the NDT will be applied in site during the next pressuring test of the VeRCoRs mock-up.

5. Acknowledgment

This project "ENDE" has been funded by the French Government project "Investments for the future" whose management has been committed to the ANR.

6. References

[SBA 2015] Sbartaï, Z. M., Boniface, A., Saliba, J., « Improvement of damage localization in concrete by acoustic emission using an adaptive meshing algorithm », *15th International Academic Conference on Engineering, Technology and Innovations (IACETI)*, Singapore, Dec 2015.

[LAR 2015] Larose E, Obermann A, Digulescu A, Planes T, Chaix J-F, Mazerolle F, and Moreau G, « Locating and characterizing a crack in concrete with diffuse ultrasound: a four-point bending test », J. *Acoust. Soc. Am*, 138 232 (2015).

[BAL 2012] Balayssac J.P and all, « Description of the general outlines of the French project SENSO – Quality assessment and limits of different NDT methods », *Construction and Building Materials*, 35, October 2012.

[MAT 2010] Matsuyama K, « On-site measurement of delamination and surface crack in concrete structure by visualized NDT», Construction and Building Materials, 24, 2381-2387, 2010.

[BUD 2005] Buddhi L., « Vibration based baseline updating method to localize crack formation and propagation in reinforced concrete members », *Journal of Sound and Vibration*, 344, 258-276 (2005).

[AGG 2011] Aggelis D. G., « NDT approach for characterization of subsurface cracks in concrete », Construction and Building Materials, 25, 3089-3097, 2011.

[WOL 2015] Wolf J., « Detection of crack propagation in concrete with embedded ultrasonic sensors », *Engineering Fracture Mechanic*, 146, 161-171, 2015.

[QUI 2012] Quiviger A and all, « Effect of the presence and size of a real macro-crack on diffuse ultrasound in concrete », *NDT&E, Int*., 45, 128-132, 2012.

[TAH 2010] Tahreer and all, « Application of Digital Image Correlation to reinforced concrete fracture », *Procedia Materials Science*, 3, 1585-1590, 2010.

[ABR 2012 2009] O. Abraham, B. Piwakowski, G. Villain, O. Durand. « Non-contact, automated surface wave measurements for the mechanical characterization of concrete », *Construction and Building Materials* , Volume 37, December 2012, pages 904-915.

[KAC 2016] Kaczmarek M., Piwakowski P., Drelich R., « Non-Contact Ultrasonic Non-Destructive Techniques: State of the Art and Their Use in Civil Engineering », *Journal of Infrastructure Systems* DOI: 10.1061/ (ASCE)IS.1943-555X.0000312. B4016003-1 - B4016003.