Non-destructive Evaluation of Containment Walls in Nuclear Power Plants

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Abstract. Two functions are regularly tested on containment walls in order to anticipate a possible accident. The first is mechanical to resist a possible internal over-pressure and the second is to prevent leakage. The AAPR reference accident is the rupture of a pipe in the primary circuit of a nuclear plant. In this case, the pressure and temperature can reach 5 bar and 180°C in 20 seconds. The national project 'Non-destructive testing of the containment structures of nuclear plants' aims at studying the non-destructive techniques capable to evaluate the concrete properties and its damaging and cracks. This 4-year-project is segmented into two parts. The first consists in developing and selecting the most relevant NDEs in the laboratory to reach these goals. These evaluations are developed in conditions representing the real conditions of the stresses generated during ten-yearly visits of the plants or those related to an accident. The second part consists in applying the selected techniques to two containment structures under pressure. The first structure is proposed by ONERA and the second is a mockup of a containment wall on a 1/3 scale made by EDF within the VeRCoRs project. Communication is focused on the part of the project that concerns the damage and crack process 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 [1], Locadiff [2], 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 data. The spatial normalization of the data in the specimen space allows proposing algorithms on the combination of the experimental data. The tests results are presented and they show the capacity and the limits of the evaluation of the volume, surface or global data. A data fusion procedure is associated with these results.

CONTEXT

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 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.

Determining the properties is done by establishing links between NDT measures and durability indicators. While Non Destructive Testing is successfully used for metal materials, the results have not been satisfying for concrete material or for civil engineering structures, notwithstanding the existence of AIEA guide or norms. Several projects have been developed to improve the control of the techniques and associated uncertainties. Structuring projects, SENSO [4], ACDC [5] and EVADEOS, have proposed new non-destructive measurement methods with proven performances. Based on this new knowledge and expertise, non-destructive testing procedures and guidelines [6] are proposed, along with a methodology to transfer NDT techniques from the laboratory to onsite applications. This data fusion based methodology [7] makes it possible to evaluate collectively several indicators and do away with their interdependence. An inversion procedure [5] allows resetting and calibration of the procedures based on onsite sampling or reference data for the auscultation of each new structure while addressing the ageing constraint.

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 [8]. It is associated with Radar but without combining the two sets of data. The ultrasonic shear-wave tomography with multiple arrays of probes in one head (commonly known as MIRA) was applied to evaluate its effectiveness in determining concrete delamination in concrete pavements, bridge columns, and concrete runways [9]. 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 [10]. Surface and through-transmission waves are also used to evaluate the quality of cracks repair by resin injection [11]. Surface waves generated by pencil lead break are also exploited to follow the growth of a crack in concrete [12]. These authors have shown that the scatter and the central frequency depend on the crack depth. They also show the ability for the simple thermographs to reveal the existence of a crack up to the depth of 11mm. The complementarity of techniques is studied to follow the propagation of a crack in a bending test [13]. 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 [2] to map the mechanical changes, fracture opening, and damage development. The crack detection and repair are also studied by coda wave interferometry [14]. The propagation of the wave is still considered as the propagation of the energy to determine the depth of the cracks by arrival time of the maximum of the energy [15].

The objective of the ENDE project 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 content of the ENDE project and especially we develop part of the work concerning the determination of the damage and the crack size and opening. The actual results of the other part that is the concrete characterization, were presented already [16]. 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. We focus on the difference of the information before and after the peak of loading that corresponds to the initiation of the crack. This time corresponds to the percolation of all the micro cracks generated by the diffused damage into a small crack that is starting to grow. We present briefly the technique implemented during the testing. To conclude we describe the results obtained by data fusion with the set of results.

PROJECT SCHEDULE

The project develops in two parallel directions: material characterization and crack detection and sizing. The work is organized in four work packages (WP): definition of the experimental plan, concrete characterization, defect characterization in laboratory and on-site application.

This first section introduces all the WPs to show the ENDE project organization and general approach. In section 3, only the WP3 tests will be detailed, due to the volume of data examined in the project.

WP1: Experimental Plan

WP1 defines the experimental plans that will be necessary for WP2 and WP3. It structures the knowledge and defines the non-destructive measurement parameters, called "observables", that will be the most relevant to evaluate the WP2 concrete durability indicators (compressive strength, elasticity modulus, porosity, water content, pre-stress evolution, thermal and mechanical damage). Note that the tests are intended to study concrete in its different states in the different stages of its life cycle. Characterization will thus be done under press with or without stress as well as on thermally damaged or undamaged specimens.

In parallel, WP3 defines the experimental principles for characterizing the transition from micro to macro crack network generated by mechanical solicitation or thermal damage. This will concern the positioning of localized diffuse damage, the development into continuous damage leading to the formation of a crack, the opening and growth of a macro crack. Knowing crack opening behavior and size is essential when dealing with gaseous transfer. Particular attention will be paid to the cracks closed under the action of pre-stressing cables and which can reopen under pressure.

WP2: Assessment of Concrete

The evolutions of the targeted indicators relate to material toughness and leakage
To represent the different concrete states, specimen conditionings are defined as follows:

- 30, 60 or 100% saturation is obtained by controlled drying in an oven
- The thermal damage cycle is performed in an oven at 20°C, 80° C, 150° C or 200°C.
- Stresses are applied under press from 0 up to 12 MPa depending on the concrete strength.

The selection of the observables that are the most sensitive and the most representative of the evolutions of the non-destructive parameters with the indicators is performed following an approach that will be explained later. This selection is based first on the sensitivity of observables to indicator evolutions, on the quality of the correlation law linking these observables with the indicators and also on their combining capabilities. The complementarity of the techniques is examined by merging the observables. The determination of a normalized inverse procedure quality estimator allows the most suitable combinations to be sorted [5]. The first results are presented in [16].

WP3: Assessment of Cracks

The goal of WP3 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 at the interfaces between steel bar and concrete, 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 50*25*12 cm^3 specimens (Fig. 1a-c). Testing of crack opening and closure under compressive loading is done on 250*25*12 cm^3 specimens (Fig. 1b).

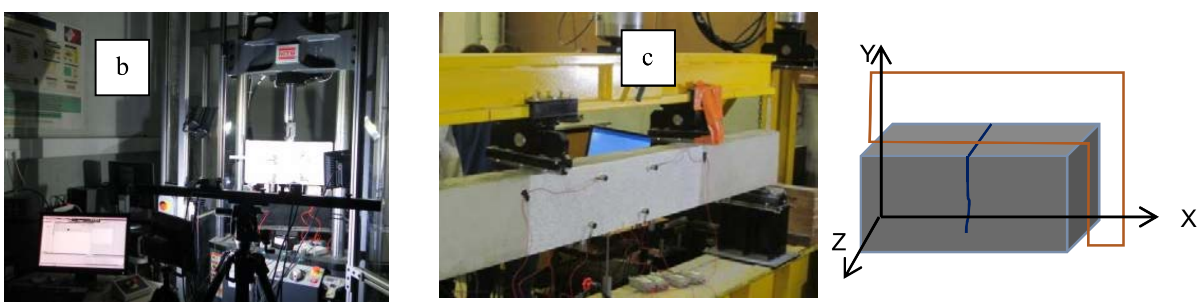

FIGURE 1. a) Follow-up testing of diffuse damage and its transition to continuous damage, b) Testing of crack opening and closure c) Sample for 3 points bending test with a crack.

The NDT techniques implemented are: surface waves [17], diffuse waves [15], localization and diffusion [2], time reversal [18], acoustic emission [1], digital image correlation [19], resistivity. WP3 laboratory tests and results will be developed in this paper.

WP3 is the follow-up of crack propagation through the analysis of the maps produced by the different non-destructive techniques. 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 1cm3. Data combinations are studied using fusion operator to compare the results of the different techniques.

WP4: On Site Implementation

Once the data from WP2 and WP3 are analyzed and the non-destructive parameters are selected, WP4 will perform measurements on real structures. Tests were carried out first on a wind tunnel available from ONERA in

June 2016. Pressurization of the wind tunnel is 3.83 bars each day (Fig. 2a). Therefore, the cracks open regularly and generate leaks. They are identified. The ONERA wind tunnel will offer the opportunity to develop innovative on-site measurements and to optimize the parameters of these measurements or of analyses. Other tests will be carried out on a mock-up developed by EDF (Electricité de France) in the VeRCoRs program. They are planned for 2017. This structure is a containment building at the 1:3 scale (Fig. 2b). It is representative of a real containment structure in terms of mechanical and saturation rate behavior. Concretes and defects are similar to those of the actual structure, and so the previously tested measurements will be implemented as if in a real NPP.

FIGURE 2. a) ONERA wind tunnel housing, b) VeRCoRs containment mock-up developed by EDF, c) Hole equipment access

The dimensions of the mock-up are: ϕ 20m, h 20m, wall thickness 40 cm. It has been created and is made available in the framework to experimentally simulate the behavior of a containment building in the event of a decennial inspection and then of a reference accident. The ENDE project tests will be run on areas identified beforehand. WP4 includes the consideration of the real measurement conditions such as the density of steel reinforcement and of pre-stress (Fig. 2c).

WP4 prepares the onsite measurement protocols: measurement implementation (type, number, repeatability, reproducibility, data format, etc.). It also prepares the logistics (20 people simultaneously) and manages the tests and the extracted data. Protocols and recommendations will be proposed, along with protocols to be exploited on site.

Note here that the concrete used for the WP2 and WP3 laboratory tests is the same as that of the VeRCoRs mock-up. Its characteristics are: strength 50 MPa, elasticity modulus 36,000 MPa and porosity 15%.

3 POINTS BENDING TEST

In this paper, we only present the tests realized in the WP3. They were developed to detect the diffuse damage and its transition to continuous damage. For that purpose, 3 points bending tests on 50*25*12 cm^3 notched specimens controlled in displacement were realized (Fig. 1a). The notch had 1cm depth and 4mm width. We focus on the difference of the information of NDT before and after the loading peak that corresponds to the development of a visible macro crack. So the time before the peak concerns the diffused damage and after the peak the detection of the crack.

A typical loading cycle of the test is presented in Fig. 3.

We have realized 4 loading-unloading cycles before the peak of load and 3 after the peak was reached. The load was increased up to different levels for which we have maintained the displacement, during 30 minutes. The NDT measurements were realized on the specimen under loading. We have unloaded the specimen between each cycle. For the three cycle after the load peak, the crack was propagate at three lengths.

We have not enough accessibility to realize all the NDT on a unique sample. So we have tested 4 specimens in order to develop all the NDT. Only the Acoustic Emission was applied on all the samples.

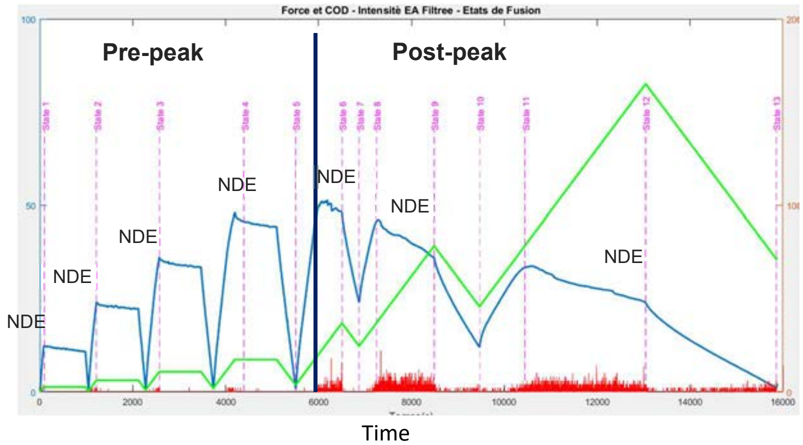

FIGURE 3. Loading cycle during the 3 point bending test. The blue line is the load, the green the crack mouth opening displacement (CMOD), the red corresponds to the events density of acoustic emission for each time.

NON DESTRUCTIVE TESTING

We present 6 techniques implemented during the bending test. They are classified in three categories that correspond to three levels of analysis:

- The local techniques that give a global information on a zone of the sample. They are the Surface Waves (SW) and the Diffused Waves (ATME)
- The surface techniques that analyze the information from the lateral surface. We obtain an image on which we are able to follow the crack during its propagation. They are the Digital Image Correlation (DIC) and the parametric image of diffused wave (DW).
- The bulk techniques that give information in the whole volume of the sample. They are the Acoustic Emission (AE) and the localization by diffusion (Locadiff)

These choices were done to get two pieces of information for each level. It is thus possible to use data fusion in order to improve the quality of the results for each dimension. Furthermore, our aim is to make surface techniques and more specially the DIC as the technique of reference. In this case we can calibrate the bulk and local techniques by using the surface techniques. This work is in development in the laboratory.

Local Techniques

The Surface Waves technique is developed with automated devices [20], [17]. The one used to follow the cracks was the robot shown in (Fig. 4a). It works with two ultrasonic air transducers (Fig. 4b). The emitter sends a wave that propagates through the surface concrete on a depth equal 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 result of the surface wave attenuation A(X) has increased roughly when the cracks crossed the path of the waves (Fig. 3c).

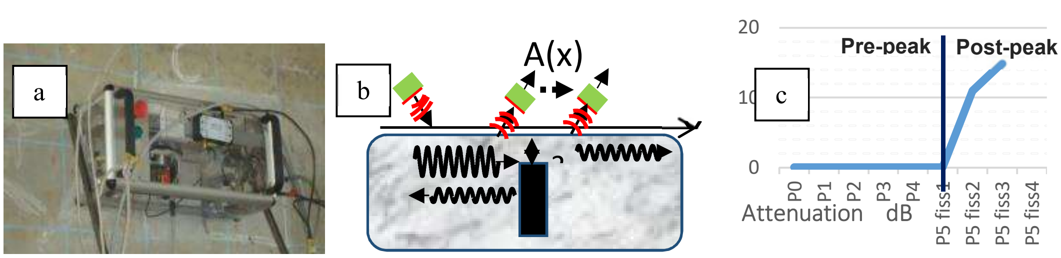

FIGURE 4. a) Ultrasonic surface waves scanner [20] b) Principle, c) Attenuation of the surface waves

The Diffused Waves technique [15] analyzes the wave energy transportation through the sample with a crack (Fig. 5a). One of the Non Destructive Parameters used is the Arrival Time of the Maximum of the Energy (ATME) shown in Fig. 5b by the blue point. We can follow the increase of the crack depth through a simple model (Fig. 5c).

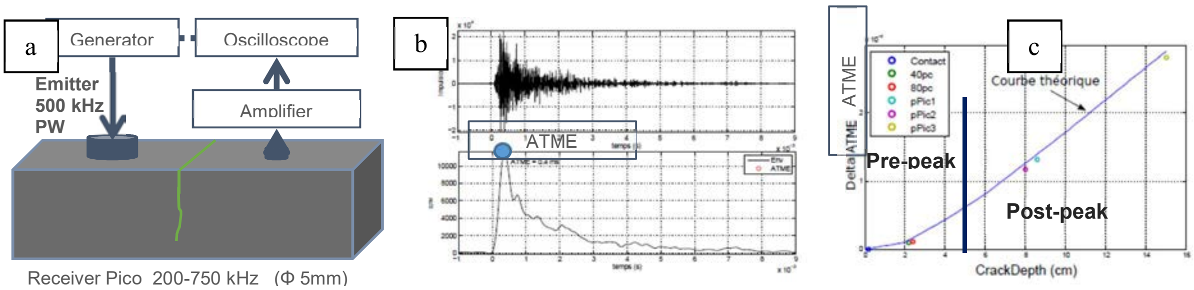

FIGURE 5. a) Diffused Waves analysis b) ATME c) Link between ATME and the crack depth

Surface Techniques

The Digital Image Correlation [19] (DIC) works with the displacement measurement of the points of a speckle pattern (Fig. 6a). 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).

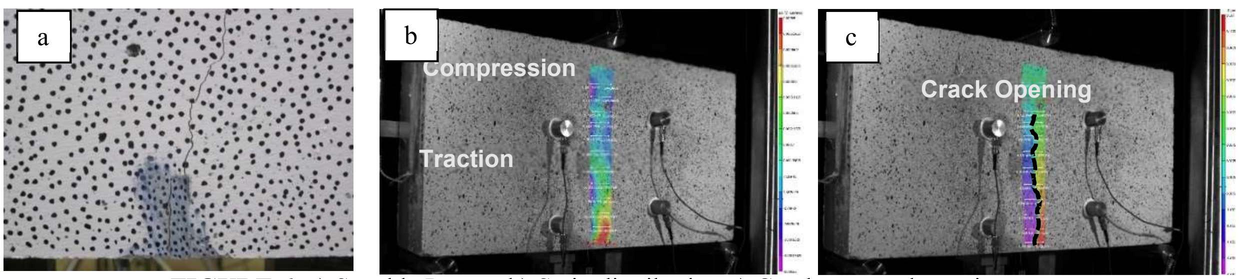

FIGURE 6. a) Speckle Pattern b) Stain distribution c) Crack way and opening

The US antenna consists to record the Diffused Waves on each point of a matrix (20*30 cm^2) by Laser Vibrometer (Fig. 7a-b). By using the covariance matrix of the signals to remove the coherent part, we can make time reversal of the diffused waves to map the energy that goes over the cracks (Fig. 7c).

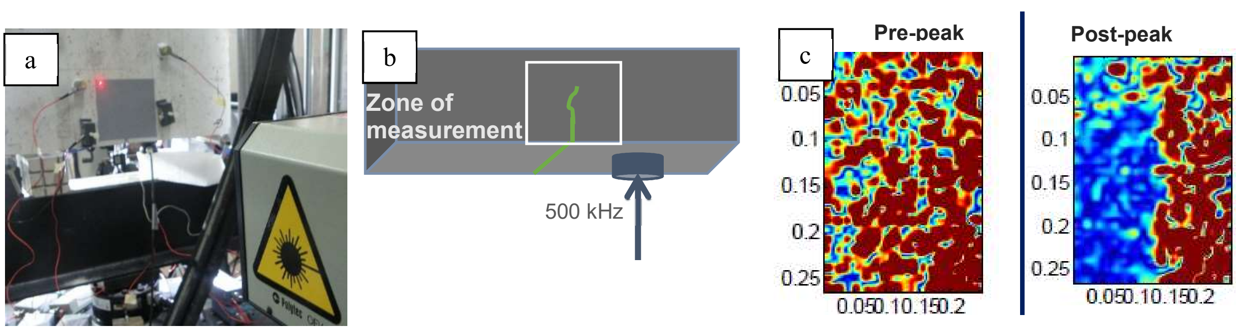

FIGURE 7. a) Us antenna measurement b) Principle c) Maps of diffused waves before and after the peak.

Bulk Waves Techniques

The Locadiff technique [2] uses the evolution of the diffused waves obtained from a transducers network (Fig. 8a: 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. 8b) and the crack length (Fig. 8c). The size of the voxels is 2*2*2 cm3.

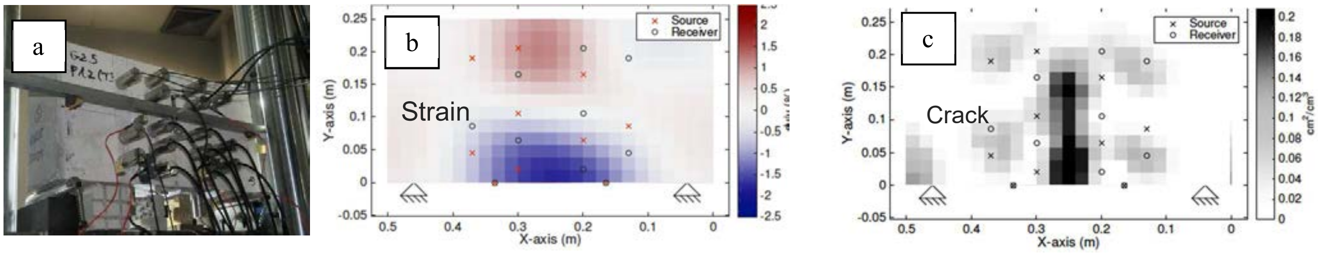

FIGURE 8. a) Transducers distribution b) Strain before the peak c) Crack propagation after the peak.

The Acoustic Emission [1] is a passive technique that allows following all the events that occurs in the sample with 8 receivers (frequency=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. 9a). The results of a continuous auscultation of one of the samples can give us the density of the damage (Fig. 9b) and or the density of the events close to the crack (Fig. 9c).

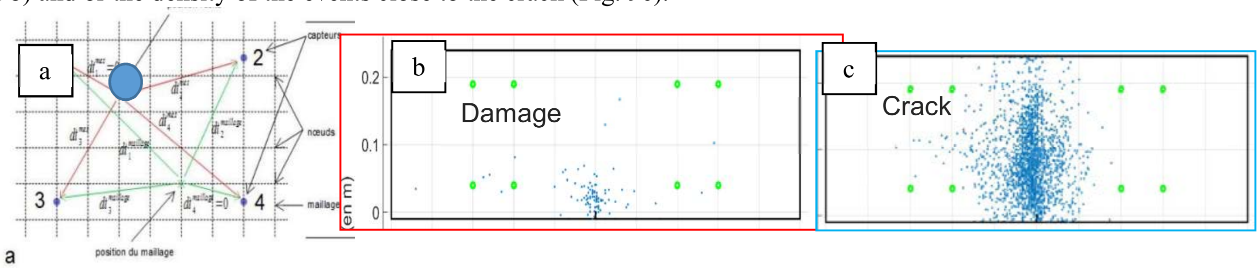

FIGURE 9. a) AE principle b) Events cumulation with damage before peak c) Events cumulation around the crack after peak

Data Content

The data obtained from the three levels of measurements allows us to get the position of the crack by Surface Wave and the length of the crack by the two local techniques (scalar data). The US antenna and DIC produce maps of the strain as well as the length and opening of the cracks (surface data). The AE and Locadiff give spatial data of all the volume.

Some techniques are applied continuously during all the test like AE and DIC.

The other techniques are developed only during the loading plateau.

DATA FUSION

The aim of the data fusion is to reinforce the confidence and the definition that we can get from the results with each technique. It was made for each information level. The DIC is considered as the most reliable of the surface information, and we assume that it is the reference technique. So we have developed a software to merge the bulk data and to compare the merged result with the DIC mapping.

The process includes 5 steps:

- Resampling the data in a unique mesh with voxels of 1 cm^3. We normalize each data set regarding its maximum value.
- Mapping of the bulk data on parallel plans to describe all the volume.
- Merging of the results of the bulk technique for the each plan of the volume.
- Comparison with the DIC map.
- Calibration of the bulk technique in order to work on site.

We have developed a software to realize the data fusion with a choice of the tools: Maximum of amplitude, Average, Hadamard Product, Dempster Schaffer [21]. We evaluate the quality of the fusion with three parameters calculated from the correlation between the two images obtained by AE and Locadiff. The parameters are the shift of the pixels' center, the mean resemblance of the pixels and the ratio between the numbers of pixels of each image that are different from 0. Figure 10a shows the data issued from the AE, Fig. 10b those from Locadiff. The images are obtained for the mid-plan of the sample.

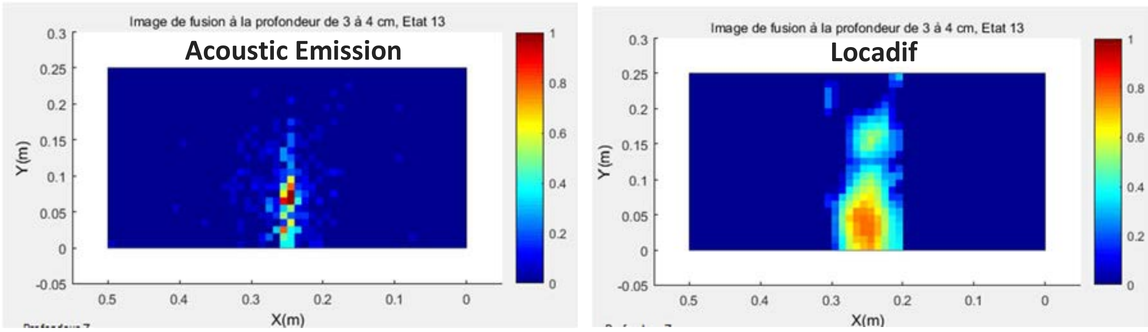

FIGURE 10. a) AE results for the mid-plan of the sample b) Locadiff results for the same plan.

The result of the data fusion calculated with Hadamard Product is plotted in Fig. 11a. It is compared with the DIC image obtained on the same sample shown in Fig. 11b.

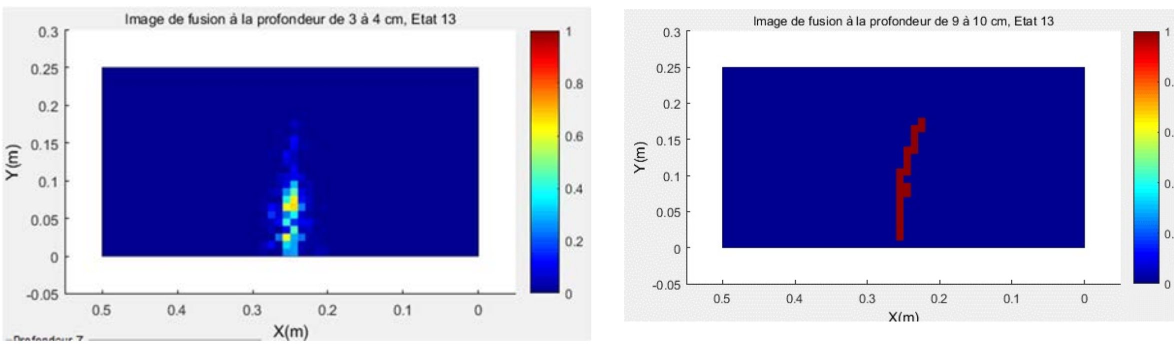

FIGURE 11. a) Hadamard Product of AE and Locadiff results b) DIC image for the same sample

The results of fusion and DIC mapping are close and we have yet to sample the bulk technique results with the DIC solution.

CONCLUSION

The ENDE project is in progress with a lot of data obtained in the two aims of work. It contributes to evaluate the two functions of the containment wall of nuclear power plant.

The first that is WP2, concerns the concrete characteristics assessment. The second, WP3, developed in this paper presents the crack and damage assessment. For WP3, we developed 6 techniques known or new. These 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 on the Onera WindTurbine in July. The data are just under treatment processing. Next, all the NDT will be applied in site in 2017 during the next pressuring test of the VeRCoRs mock-up.

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