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NON DESTRUCTIVE MONITORING OF MECHANICAL STRESS IN CONCRETE FOR THE SURVEY OF NUCLEAR POWER PLANTS

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ABSTRACT

To prevent consequences of damage in case of accident, some barriers of pre-stressed concrete are included in the nuclear power plant structures. Hence, to insure the nuclear security, it is important to control these structures. The nuclear accident induces pressure and temperature increases. This case is studied in a French Project involving eight academic and industrial laboratories with skills in NDE (Non-Destructive Evaluation) methods. In this paper, we focus on the synthesis for the results with different techniques in relation with the evolution of stress in the structure. Experiments tests have been conducted on slabs 0.5 m x 0.25 m x 0.12 m submitted to compressive load, for one concrete mix formulated to be representative of nuclear containment. In situ NDE measurements have been done during a test simulating nuclear accident. These experiments were realized on the Vercors mock-up which is a 1/3 scaled concrete power plant (ϕ 16 m x h 30 m cylinder, with 0.40 m thick walls) submitted to internal pressure up to 4 bars. This study includes electromagnetic techniques such as radar, capacitive, resistivity, permeability and ultrasonic measurements (impact echo, ultrasonic pulse velocity for volume and surface waves, diffuse waves, coda wave interferometry, nonlinear acoustics, etc.). Good agreements are observed between laboratory and in situ measurements. Industrial and research perspectives are presented.

Keywords: Non-Destructive Evaluation, Concrete, Nuclear power plant, Mechanical stress, Ultrasonic, Electromagnetic.

1. INTRODUCTION

The function of concrete containment walls is to withstand sudden increases in internal pressure and temperature during an accident or during external aggressions that may be environmental (floods, tsunamis, earthquakes, etc). The objective of the ANR French research project “Non-Destructive Evaluation of containment nuclear plant structures” (ENDE) is to evaluate concrete characteristics that allow a better estimate of the risks of rupture in cases of severe stress [1, 2].

During its life cycle the concrete containment walls could evolve under different thermal and mechanical loading. The NDE techniques aim to detect the first state of these evolutions in the frame of the surveys. Successful results have been obtained in previous projects [3, 4] with regard to elastic modulus, porosity and water content. In these previous works the influence of a mechanical solicitation is voluntarily ignored. A part of the ENDE project aims to follow, with non-destructive measurements, compression stress evolution due to the post-tensioning cables during a decennial test where the compression stress inside the concrete wall is reduced due to an increase of the air pressure inside the containment structures up to 4.2 bars. Knowing the influence of the mechanical loading evolution makes it possible to follow micro-structural evolution which could appears under thermal or other external aggressions.

In this paper the influence and quantification of stress are studied for different NDE techniques in laboratory and in the *in situ* where the measurement conditions could be degraded.

2. MATERIALS AND METHODS

The NDE measurements were carried out in laboratory on concrete slabs for a first time, then on site on the Vercors mock-up which is a 1/3 scaled concrete containment structure.

Fourteen NDE techniques have been implemented by the academic partners: Torrent permeability [4], electromagnetic method as capacitive technics or RADAR [5], electric resistivity [6], longitudinal and transverse waves in transmission mode or Ultrasonic Pulse Echo [8], Impact Echo [9], surface wave [10], diffuse wave [11], Dynamic Acousto Elastic Technique [12], Temporal Reversal method for Evaluation Non Destructive [13], Coda Wave Interferometry [14] and Nonlinear Coda Wave Interferometry [15].

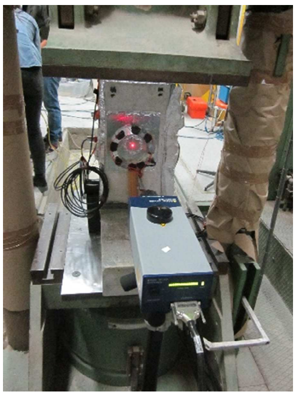
2.1 Laboratory tests

Laboratory test were made on concrete slabs of 0.5 m x 0.25 m x 0.12 m dimension with the same formulation of concrete used for the Vercors mock-up which is representative of the ones used for nuclear power plant structures. These dimensions make it possible to limit edge effects while maintaining homogenization times (temperature, water content, etc.) and handling conditions reasonable. These specimens were put in a press and submitted to successive compressive loadings at levels of less than 30% of the compressive strength. These stress experiments were followed each time by the Coda Wave Interferometry (CWI) method that showed the first load induced irreversible damage. Other loads showed reproducible evolution without hysteresis phenomenon. Following this observation, it was decided to compare the NDE methods only after two pre-loading cycles, while taking care not to exceed the maximum loading value of the first load. It also makes it possible to dissociate the effects of the mechanical loading from the microstructural effects that take place during the first loading. All loads were done up to 8 MPa.

Resistivity

Ultrasonics Surface Waves

Ultrasonic Diffusion



CWI and TREND methods on slab under compressive load

FIGURE 1: EXAMPLES OF NDE METHODS APPLIED ON LABORATORY SLABS

Figure 1 (up) shows different example of used NDE method. Figure 1 (down) illustrates the case of CWI and TREND measurements during the compressive loading of a slab.

2.2 In situ measurements

In situ measurements took place on Vercors mock-up which is a structure built by EDF (Figure 2) representative of the mechanical and durability behaviors of a real nuclear power plant including defects and concrete mix (Compressive Strength = 50 MPa, Young's Modulus = 36000 MPa and porosity = 15 %). Its dimensions are: diameter = 16 m, height = 30 m, wall thickness = 0,4 m. Vercors makes it possible to experimentally simulate, in an accelerated time, the behavior of containment walls after of a series of 10-years pressure tests and ultimately in the case of a reference accident.

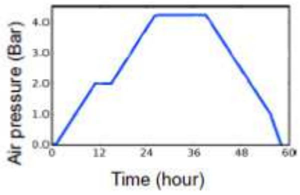
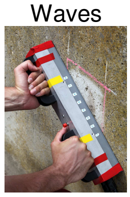


FIGURE 2: VERCORS MOCK-UP AND PRESSURE CYCLE

The same NDE technics were applied on the Vercors structures at the same points to be compared. Figure 3 shows examples of measurements realized on the concrete wall of the containment structure. The measurement area was defined by a grid of four lines (A, B, C &, D) and five columns (from 1 to 5).

RADAR

Surface Waves



Impact Echo

Permeability

FIGURE 3: EXAMPLES OF NDE METHODS APPLIED ON VERCORS MOCK-UP DURING PRESSURE LOAD

3. RESULTS AND DISCUSSION

We show on figure 4 (Surface waves velocity) and 5 (Diffusivity of diffuse waves) results for the same technics obtained on concrete slab and on the Vercors mock-up.

Figure 4 shows the result obtained for the surface wave velocity on slabs under compressive load and on the Vercors mock-up during internal air pressure loading. We can observe an expected increase for velocity with the compressive stress and the decrease of the velocity with the internal air pressure. These results are coherent due to the fact that the increase of internal air pressure induces decrease of the initial compressive stress in the wall of the Vercors mock-up. The amplitudes of variations are very similar in the two different experiments and that could predict a decrease of the initial compressive in the Vercors wall of 5 to 8 MPa during the internal air pressure increasing up to 4.2 Bar.

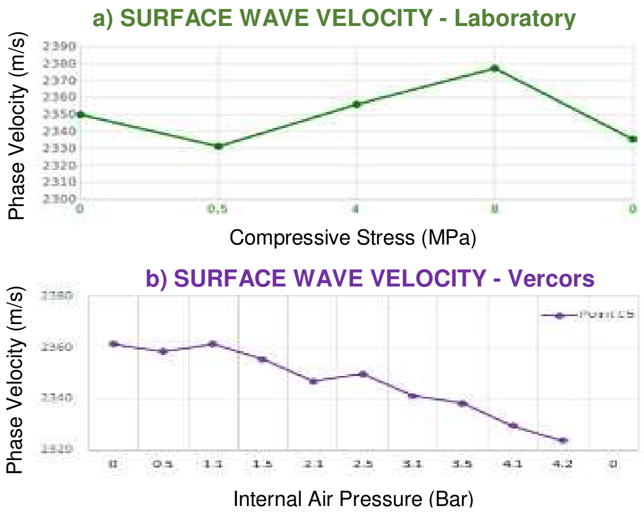


FIGURE 4: EVOLUTION OF SURFACE WAVE VELOCITY a) VERSUS STRESS, b) VERSUS INTERNAL AIR PRESSURE

Figure 5 shows the results obtained for the diffusivity parameter of diffuse ultrasounds in laboratory condition on the Vercors site. The opposite variations (increase with compressive stress and decrease with internal air pressure) in the two experiments are also expected. We also observed different behavior on the Vercors wall between two different points.

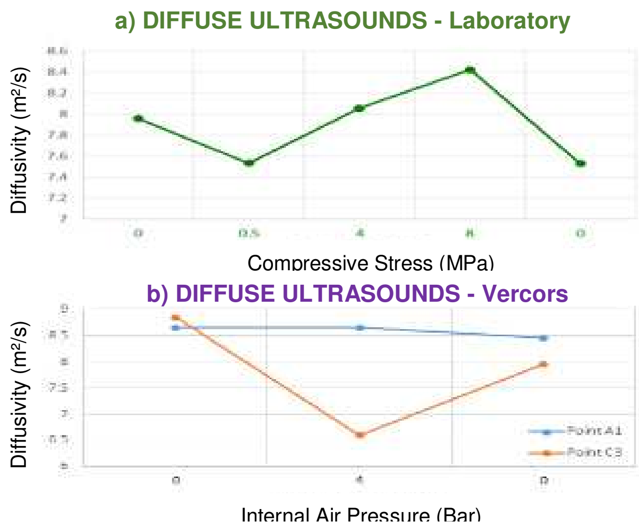


FIGURE 5: EVOLUTION OF DIFFUSIVITY a) VERSUS STRESS, b) VERSUS INTERNAL AIR PRESSURE

These results, representative of results obtained in ENDE project, demonstrate the possibility to evaluate the mechanical stress in Laboratory conditions and show possibilities to do the same thing in case of monitoring in the *in situ* configuration.

4. CONCLUSION

The aim of ENDE project is to study tomorrows' NDE techniques that can be implemented on concrete nuclear containment walls. Ultrasonic waves are very present in the techniques tested because of the targeted mechanical indicators. electromagnetic and electrical techniques seem to be non-dependent to mechanical stress and so there are essential to get information about concrete water content. In view of the difficulty of evaluating the stress in laboratory conditions and *in situ* on the Vercors mock-up, it is recommended to work on the implementation of permanent NDE sensors.

ACKNOWLEDGEMENTS

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