Detection and evaluation of macro-cracks and micro-cracking by using automated surface wave non-contact scanners

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RESUME.

The goal of the presented work is the detection and evaluation of cracks, in the VeRCoRs mock-up which constitutes the double-wall containment building of a Nuclear Power Plant in scale 1/3. The experiments are conducted in situ, on the inner wall of the VeRCoRs mock-up. The detection is performed by means of two automated scanners designed for the non-destructive non-contact control of concrete using surface waves (SW). The SW signal assures the penetration in a concrete wall between 1 to 60 cm. The scanners provide the non-contact measure which permits to avoid a modification of the concrete surface by a coupling agent and a time-consuming coupling procedure. The results, obtained during pressure test in the VeRCoRs mock-up, prove that the scanner can be successfully used in the detection of micro-cracking, of cracks location, the evaluation of their opening and of the progressive ageing of the mock-up.

Mots-clefs: Automated NDT, concrete, surface waves, cracks, velocity, attenuation, non-contact.

I. INTRODUCTION

The paper presents the research conducted in the frame of the French research project "Non-Destructive Evaluation of Containment Nuclear Plant Structures" (ENDE) in the period of 2015-2020. The project aims to develop the Non-Destructive Testing techniques that can be applied to evaluate and monitor the concrete in containment enclosures. [Garnier et al.2018]. The presented experiments were carried out in the VeRCoRs containment mock-up which constitutes the double wall containment building of a nuclear power plant in scale 1/3 [Henault et al.2018].

The common feature of the method presented in this paper is the use of acoustic surface waves (SW). They propagate along the surface of the inspected material and their depth of penetration d_p is frequency-dependent and is close to SW wavelength. Therefore, the concrete wall can be examined in two scales:

(1). The evaluation of concrete through the total thickness of the examined wall. This task is realized by the recently developed Low Frequency Surface Wave scanner (LFSW) which provides

6cm < d_p < 60cm. (Fig.1.a) [Piwakowski et al.2019].

(2). The evaluation of properties of the concrete cover that is of the layer between the rebar's and the wall surface requires d_p < 5cm. This objective is accomplished by the High Frequency Surface Wave scanner (HFSW) (Fig.1.b) which is the "older brother" of the (LFSW). This scanner has been in practical use for 8 years [Piwakowski & Safinowski,2009, Abraham et al,2012]

Both scanners allow fully non-contact measurements which avoid a modification of concrete surface by a coupling agent and a time consuming coupling procedure.

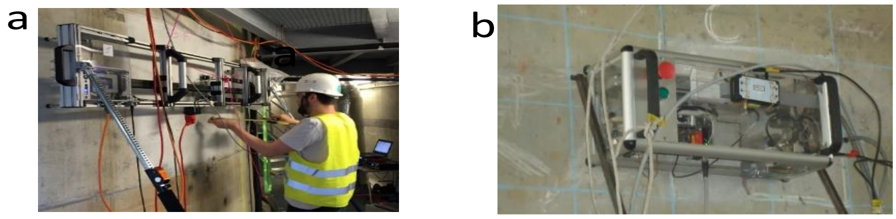

FIGURE 1. **(a) The LWSF scanner during leakage test in VeRCoRs mock up . (b) The HFSW scanner during leakage test in VeRCoRs mock up.**

II. RESULTS

A. Imaging and tracking of cracks during the pressure test in VeRCoR

The experiments were performed automatically by using LFSW scanner in VeRCoRs during the complete cycle of the pressure test carried out in March 2019 at a zone displaying two known macro cracks at positions 39 and 107 cm in the gusset lower part (Fig.2.a). During this test, the internal pressure increases up to 4 bars (Fig.2.d), and then decreases. The crack position is detected by the specially introduced $\alpha_{local}(x)$ which express the local SW attenuation and is defined as the modulus of the transfer function between SW signals recorded at neighboring points.

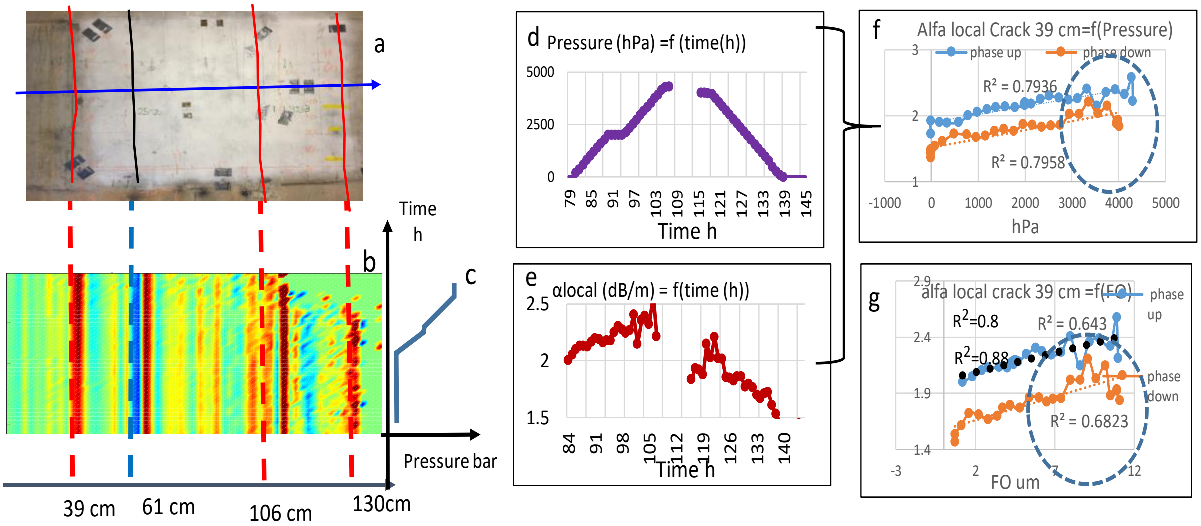

FIGURE 2. **(a) Inspected concrete wall with positions of known cracks: in red: cracks seen at the surface, black: unknown further discovered); (b); α_{local} *(x,t)* as a function of profile position and of time for increasing pressure (c) Symbolic plot of the internal pressure (see Fig.2.d). (d) Internal pressure during the test; (e) α_{local} *(x=39 cm,t)* as a function of time; (f) α_{local} *(x=39 cm)* as a function of pressure; (g) correlation between α_{local} *(x=39 cm)* and crack opening determined by Fiber Optics measurements.**

An example of α_{local} (x,t) obtained during pressure increase is shown in in Fig.2.b. It can be seen that maxima's of α_{local} (x, t) observed at positions 39 and 106 cm correlates well with the position of cracks. This shows that this parameter can be used to detect the crack position. Additionally, the previously unknown crack was found at 130 cm (its presence was confirmed optically). During the construction of the VeRCoRs, fiber optic (FO) cables were embedded in concrete which enabled the monitoring of the evolution of crack opening, expressed in micrometers [Henault et al.2012]. It can be seen that for the crack at position 39 cm the α_{local} and internal pressure correlate well ((Figs 2. d,e,f)). The correlation of α_{local} with *FO* (Fig.5.f) is quite good as well, thus showing that the value of α_{local} parameter is proportional to the crack opening.

B. Evaluation of the global crack activity during the pressure test in VeRCoR in the cracked zone

The signal recorded by LFSW scanner can be also used in order to determine the global velocity V_{sw} of the SW wave. The term *global* indicates that the estimated V_{sw} characterizes the total width of the inspected zone (here 1.5 m). Figure 3.a shows the velocity decrease is also very well correlated with the *FO* parameter during one pressure test thus showing that the V_{sw} is also directly related with the cracks opening. These measurements were conducted in the same zone during 3 pressure tests in 2017, 2018 and 2019. Figure 3.b shows the obtained limit velocities V_{swmax} (pressure = 0 and V_{swmin} (pressure = 4000hPa). It is clearly seen that both values decrease with time. This could be explained by the coupled effects of concrete drying and cracks opening and/or micro-cracking increase each year. Finally, the V_{swmin} and V_{swmin} observed as a function of time could be used as a concrete aging indicator.

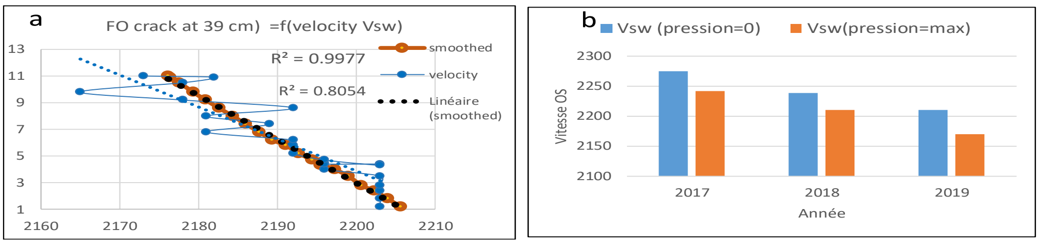

FIGURE 3. **(a) *FO* as a function of V_{sw} ; (b) V_{swmax} and V_{swmin} obtained during the successive leakage tests in the years 2017, 2018, 2019.**

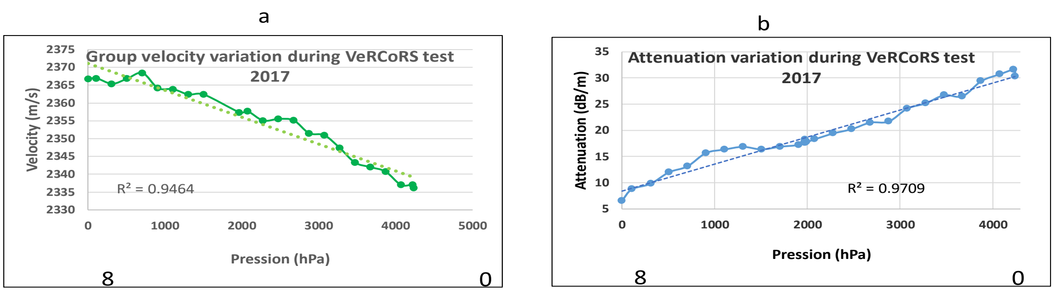

FIGURE 4. **(a) Global SW velocity in a crack free zone during the leakage test in VeRCoRs in March 2017 as a function of increasing pressure; (b) same for SW attenuation**

C. Evaluation of stress and micro-cracking during the pressure test in VeRCoRs macro-crack free zone

The measurements were performed by using the HFSW scanner (thus in concrete skin) in VeRCoRs, in March 2017, in a macro-crack-free zone. The acquisition was carried out for 12 hours with an interval of 1h during the first cycle of pressure increase. As obtained before for the cracked zone, V_{sw} decreases with the pressure (Fig.4.a), and global attenuation α_c increases (Fig.4.b) thus confirming that both quantities V_{SW} and α_c can be used to monitor the stress in concrete and /or the related micro cracking. Note that α_c is found to be much more sensitive: its variation is close to 500% but velocity variation is of 1.3% only.

III. CONCLUSION

The obtained results prove the utility of the two automated SW scanners for the monitoring the concrete.

- They permit to detect the cracks, follow the micro-cracking, and finally monitor the internal stress. They can cover the thickness of inspected wall at depth ranging from 1 to 60 cm.
- They give coherent results with embedded techniques like fiber optics and thus enable to follow qualitatively the cracks evolution during the monitoring of structures not equipped with fiber optics (if the SW penetration exceeds the crack depth).
- They display the ability to detect very small crack openings of a few micrometers. It makes it possible to use this approach in nuclear industry as well in other civil engineering applications where crack openings are greater (order of 100 micrometers).
- The non-contact operation potentially enables the automatic scanning of greater surfaces just like containment walls, bridges, beams etc. They can operate automatically; without operator's presence so are well adapted for the NDT monitoring.
- Both scanners constituent prototypes which can be easily implemented to industrial use.

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