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Inspection of Concrete/Steel/Concrete pipes by ultrasound methods affected by corrosion

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Abstract

Non-destructive ultrasound methods are developed to detect holes and assess remaining steel thickness in concrete/steel/concrete pipes affected by corrosion. Two types of methods are studied using bulk waves and guided waves on different samples in laboratory. For bulk waves, we performed measurements through concrete using pulse compression methods and a specific signature of holes in the steel layer was successfully identified. For guided waves, a numerical study enables to identify a mode sensitive to the remaining steel thickness. These first results are promising and complementary for the inspection of concrete/steel/concrete pipes on site.

Keywords: Concrete/Steel/Concrete pipes, ultrasounds, corrosion, pulse compression methods, guided waves

1 Introduction

Concrete/Steel/concrete pipes are used in French nuclear powerplants. These pipes are composed of three layers: an internal layer of centimeter concrete, a middle layer of millimeter steel and an outer layer of centimeter reinforced concrete. Samples of these pipes are shown in Figure 1 and their dimensions in Figure 2.



Figure 1: Pictures of a sample of a concrete/steel/concrete pipe



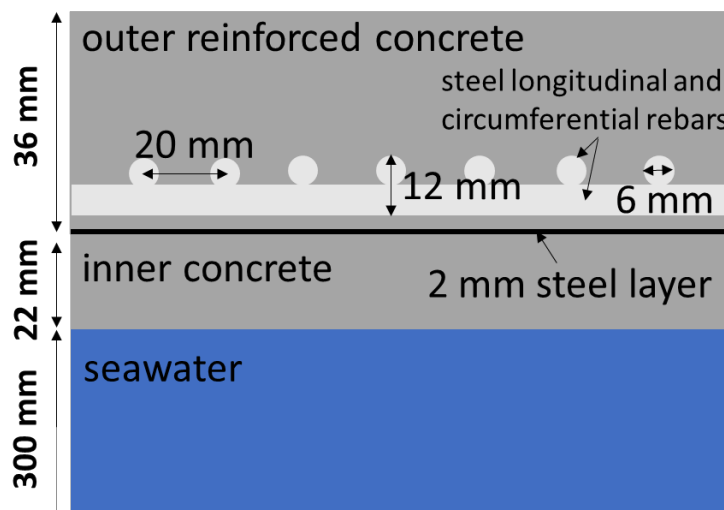


Figure 2: Dimensional data from a sectional view

The pipes located on site by the sea transport seawater. Consequently, they are affected by corrosion of the steel layer caused by diffusion of chlorides through the inner concrete layer. In Figure 3, pictures illustrate the corrosion on the inner and outer faces of a steel layer after removing the inner and outer concrete layers from a pipe sample coming from a real site. On the inner side of the steel layer, corrosion is spread over several tens of centimeters while on the outer side corrosion is only present around a hole in the steel layer. Today, on-site inspections are carried out with electrochemical measurements from the outside of the pipe [1]. The results provide a qualitative indicator only sensitive to corrosion of the outer side of the steel layer.



Figure 3: Pictures of corroded steel pieces, (a) inner side and (b) outer side

The role of the steel layer is to ensure the pipe watertightness and its mechanical strength. Watertightness is lost as soon as a hole appears in the steel layer. A mechanical study concluded that, for the pipe to keep its mechanical strength, the smallest hole that needs to be detected is 1 cm diameter and that the minimum average remaining steel thickness is 800 μm . These last criteria define the goal to achieve with an efficient non-destructive technique which must be conducted from the outside of the pipe under working conditions, that is the pipe is filled with water.

To meet this industrial goal, ultrasound bulk waves, ultrasound guided waves and vibration techniques are investigated. In this paper, results obtained with both bulk and guided waves are presented. Lab specimens (shown in Figure 4) composed by individual concrete and steel layers

were used. They are 30 cm x 30 cm flat plates with a thickness corresponding to the ones given in Figure 2. A hole of 1 cm diameter was drilled in the center of the steel plate. Material properties are presented in Table 1. The samples can be handled easily. Measurements can be performed on the individual samples or on layer assemblies. They can be immersed in water if needed. In this preliminary study, some experimental measurements are compared to simulation results. Corrosion products, which are a porous water saturated medium, are modelled by water.

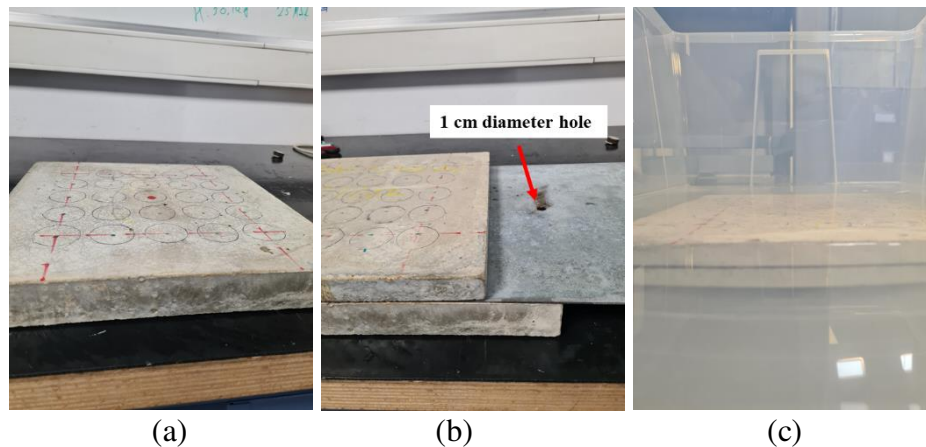


Figure 4: Pictures of (a) concrete lab flat plate sample, (b) a concrete/steel/concrete assembly and (c) a concrete/steel/concrete assembly immersed in water. The steel plate has a 1 cm diameter hole in its center

Table 1: Material properties

Material	V_p (m.s ⁻¹)	V_s (m.s ⁻¹)	ρ (kg.m ⁻³)
Concrete	4950	3150	2440
Steel	5710	3220	7800
Water	1480	-	1000

2 Ultrasound Bulk waves

The traditional way to inspect a structure is to perform bulk waves measurements in reflexion with a P-wave transducer. The diagram on Figure 5 represents two configurations: when the transducer is above a sound area and when the transducer is above a hole in the steel layer. Considering the material properties given in Table 1, arrival times of specific echoes can be calculated. In the sound area, the first echo comes from the outer concrete/steel interface at a time of 14.5 μ s. A second interesting echo comes from the steel/inner concrete interface and its arrival time is 15.2 μ s. The time difference between these two echoes is of interest because it can enable to assess the steel thickness. For this configuration, the time difference is only of 0.7 μ s. To resolve these 2 echoes, the signal frequency must be above 3 MHz. If the steel thickness is reduced, the echoes will be closer, and the signal frequency will have to be increased. This is a real issue because at these frequencies, the wavelength is far smaller than the concrete aggregates size: multi-scattering on aggregates occurs and increases the signal attenuation [2]. When the steel layer is locally completely corroded, a hole appears. A first echo comes from the outer concrete/water interface at an arrival time of 14.5 μ s. A specific echo comes from the

water/inner concrete interface at an arrival time of 17.3 μ s. The time difference is then 2.8 μ s. The two echoes can be resolved if the signal frequency is above 1 MHz. Considering the previous arguments, bulk waves could be used to identify holes in the steel layer. The challenging issue is how to perform measurements with enough energy to go through the concrete layer where multi-scattering occurs. We tested two methods, namely pulse echo method [3] and pulse compression method [4], on a concrete/steel/concrete assembly immersed in water composed by flat plate elements illustrated on Figure 4c. The steel plate has a 1 cm diameter hole in its center. We used a 1 MHz transducer of 1 inch diameter. First, the transducer was placed above a sound area and then it was moved above the hole.

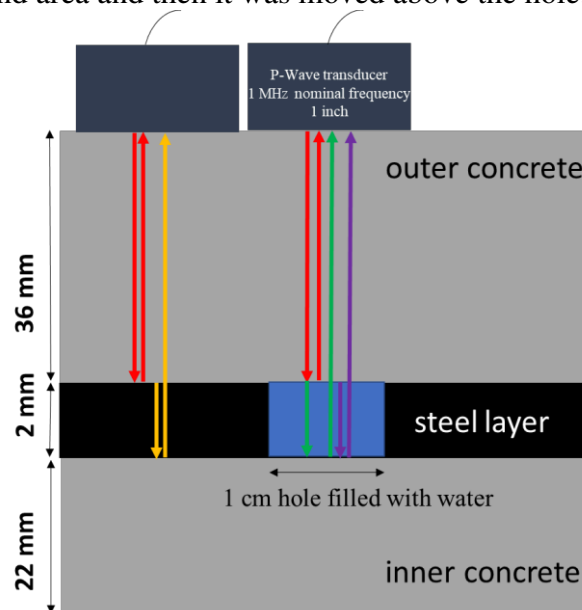


Figure 5: Diagram describing reflection measurements for two configurations: when the transducer is above a sound area and when it is above a hole in the steel layer

Figure 6 shows the results for the pulse echo method where the transducer of 1 MHz nominal frequency is stimulated by a pulse signal. When the transducer is above 3 sound areas and above the hole, a common echo is observed at around 15 μ s which corresponds to the outer concrete/steel and outer concrete/water interfaces. After this echo, slight differences are observed between the two signals, but no other echo is identified. This method doesn't enable to detect a hole in the steel layer.

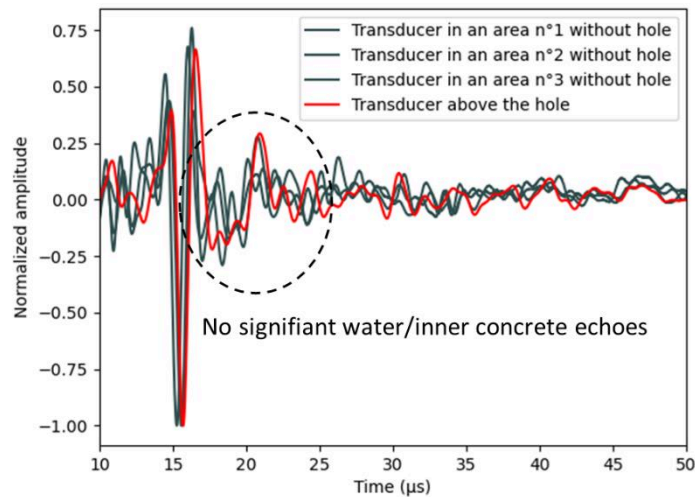


Figure 6: Pulse Echo measurement in reflection on a Concrete/Steel/Concrete assembly at 1 MHz

The signal-to-noise ratio and the signal resolution can be improved by using coded signals. The most used method of pulse compression is frequency modulation.

Typically, a Chirp signal whose frequency increases linearly with time is used to excite the transducer. The received signal is processed by an autocorrelation. The signal energy is conserved but its temporal support has been compressed and each echo is concentrated on a duration inversely proportional to the frequency band of the Chirp. Thus, the peak power after compression is significantly greater than before compression and echoes can be resolved in time. The power gain due to compression is proportional to the product of the duration of the Chirp with its frequency bandwidth.

In practice, to increase the power gain, we can therefore play on:

- the frequency bandwidth, which is chosen as wide as possible but is limited by the bandwidth of the transducer and the attenuation and multi-scattering of the concrete,
- the Chirp duration which is chosen as long as possible. The limit here is related to the storage capacity of the devices in the measurement chain. For example, a Chirp signal of 5 ms duration sampled at 20 MHz contains 100 000 points.

To implement this method, a Chirp of 5 ms duration from 100 kHz to 2 MHz was generated. This signal was loaded on a signal generator which transmitted this signal onto a 1 MHz piezoelectric sensor of one inch diameter. The Chirp was apodized by a Hanning window to limit the amplitude of secondary lobes after autocorrelation.

In Figure 7.b, the result of a reflection measurement on concrete/steel/concrete assembly with the Chirp method is presented. A first echo from the outer concrete/steel interface is observed at about 15 μ s. Besides, two other echoes can also be observed at about 19.2 μ s and 22 μ s. They correspond to multiple echoes from the water/inner concrete interface. The time difference between these 2 echoes is 2.8 μ s which corresponds to a 2 mm water thickness considering the water velocity given in Table 1.

This is a promising result for the detection of holes larger than 1 cm in diameter in real structures. Measurements are in progress to improve this result and to have a better temporal resolution and signal to noise ratio.

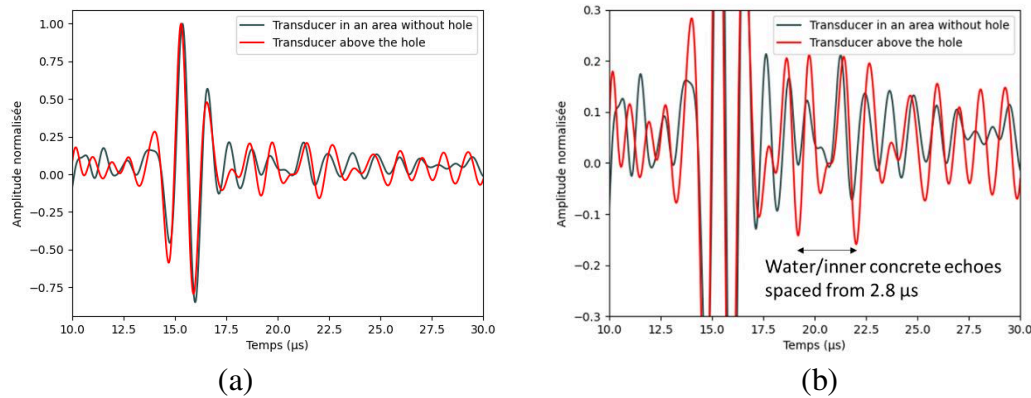


Figure 7: (a) Autocorrelation of a pulse compression measurement in reflection on a Concrete/Steel/Concrete assembly above and next to a 1 cm hole in the steel part with a Chirp signal between 100 kHz and 2 MHz and (b) a zoom on the water/inner concrete echoes

3 Guided Waves

Guided waves could be used to assess the thickness of the steel layer if we can emit and measure a guided mode sensitive to this parameter.

A parametric simulation study was carried out with CIVIA[®] [5] to identify such a mode. The simulations were conducted for frequencies above 20 kHz. Hence, the wavelength is smaller than the pipe diameter which allows us to simplify the configuration by considering plates. The upper limit is empirically fixed to 200 kHz, to avoid the presence of too many modes, which may prevent a good modal selection [6]. The simulation was conducted considering homogenized concrete which is justified as wavelength is several times greater than the aggregate size which is less than 8 mm.

Dispersion curves corresponding to a concrete/steel/concrete assembly with the material properties given in Table 1 and thicknesses given in Figure 2 were first calculated. Then, the steel thickness was decreased from 2 mm to 0 mm. As we assume that corrosion products can be modelled by water, steel loss was replaced by water. Consequently, the water thickness evolved from 0 mm to 2 mm.

Dispersion curves obtained for some steel thickness values are shown in Figure 8.a.

We observe that the Lamb 4 mode is sensitive to steel thickness.

Moreover, by plotting the phase velocities at 140 kHz versus steel thickness for this mode in Figure 8.b, we observe a linear variation of the phase velocity, from 2 mm to 1.5 mm steel thickness, with an overall variation of about 900 m/s which is very promising. The sensitivity to steel thickness depends according to the properties of the assembly, but the Lamb 4 mode is always the most sensitive between 20 kHz and 200 kHz.

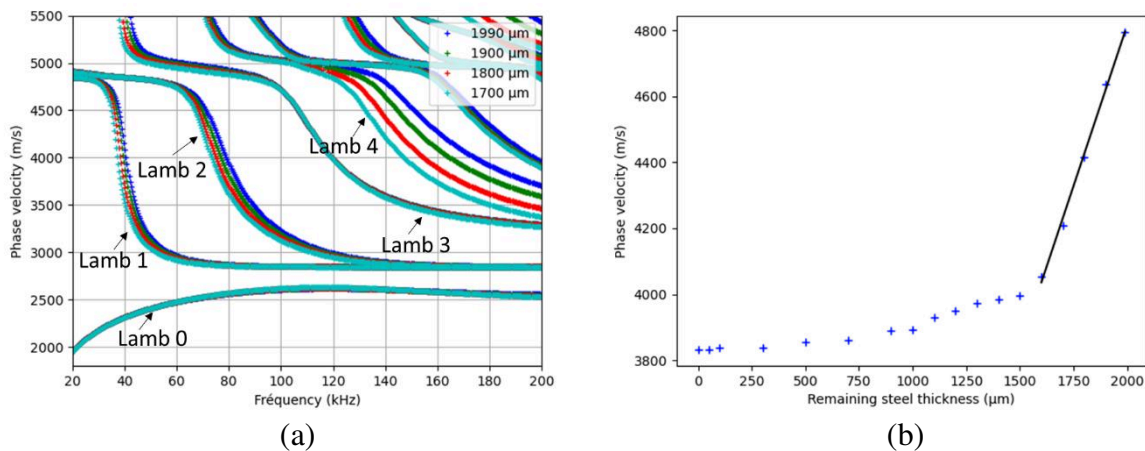


Figure 8: (a) Dispersion curve of the concrete/steel/concrete assembly for different steel thicknesses and (b) the phase velocity point at 140 kHz for the Lamb 4 mode

Before trying to measure this Lamb 4 mode on a concrete/steel/concrete assembly, a first feasibility test was performed on a concrete plate to measure the asymmetric 2 mode (A2). By abuse of language, the expressions "quasi asymmetric" or "quasi symmetric" are sometimes used for a Lamb mode. From this abuse of language, the targeted Lamb 4 mode can be called as a quasi- asymmetric 2 mode.

The measurements were performed on a 30 cm x 30 cm x 3.6 cm concrete sample. The active source was a 1.5 inch P-Wave transducer with a nominal frequency of 100 kHz which was placed on a plexiglass wedge. Its angle of 26° was calculated from the Snell-Descartes law to optimize the measurement of the A2 mode at 100 kHz. The receiver was moved every 1 cm over a distance of 20 cm.

Two series of measurements were carried out. First, the receiver was identical to the emitter, i.e. a 1.5 inch P-wave 100 kHz transducer on a 26° plexiglass wedge. Then, the receiver was a 1 inch S-Wave 100 kHz transducer without wedge.

The dispersion images were calculated with a p-w transform [7], equivalent to a 2D-FFT [8]. For each frequency, the first two maxima were extracted to assess the dispersion curves.

Results from the measurements with the emitter and the receiver on the wedges are given in Figure 9. We observe on the dispersion image in Figure 9.c that several modes can be measured.

Dispersion curves from the two series of measurements are shown on Figure 10. Theoretical dispersion curves were calculated with CIVA[®]. They are indicated with blue lines for the symmetric modes and with pink lines for the asymmetric modes.

We observe that experimental dispersion curves are in good agreement with the theoretical ones. We also observe that measurements performed with the S-wave transducer are more sensitive to the A2 mode than with P-wave. Above 135 kHz, even with the S-wave transducer, the S2 mode seems to predominate over A2. In the case of the assembly, these two modes are more distinct (Figure 8.a) and therefore the Lamb 4 mode could be measured over a sufficient frequency range. These first results are very promising for the ongoing study.

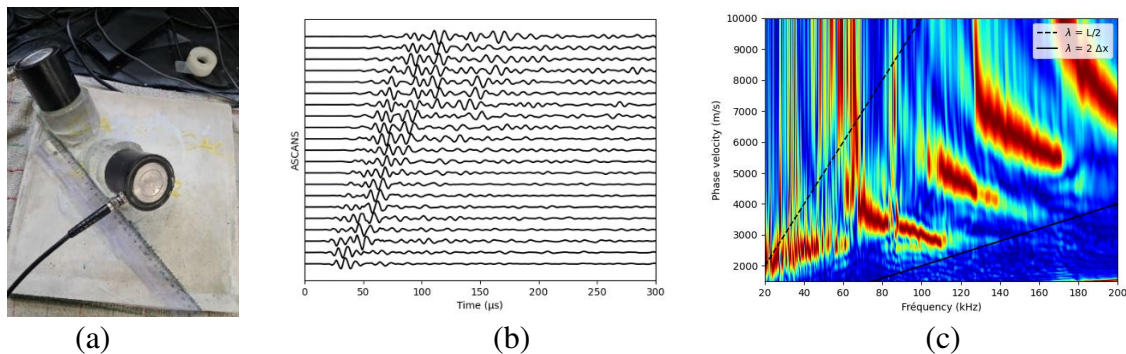


Figure 9: (a) Photo of guided waves measurements on a concrete sample, (b) set of signals in the time-distance domain and (c) the dispersion diagram after a p-w transform

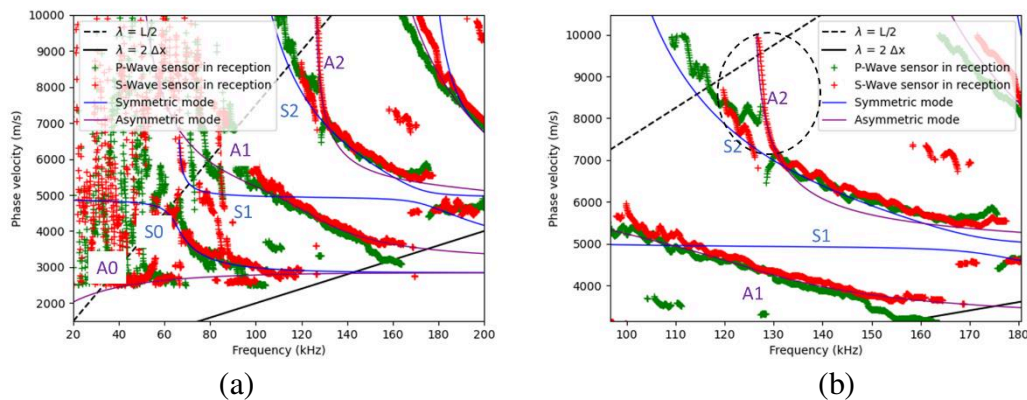


Figure 10: Comparison of the theoretical dispersion curves with the two series of measurements: P-Wave sensor in reception (in green) and S-Wave sensor in reception (in red) and (b) a zoom on A2 mode

4 Conclusion and perspectives

Non-destructive ultrasound methods are developed to detect holes and assess remaining steel thickness in concrete/steel/concrete pipes affected by corrosion. Bulk waves and guided waves methods have been studied to meet the industrial need.

With the bulk waves, the pulse compression method using a chirp from 100 kHz to 2 MHz has allowed to detect the presence of a 1 cm hole filled with water in a concrete/steel/concrete assembly. This is a promising result for the detection of holes larger than 1 cm in diameter in real structures. Measurements are in progress to improve this result and to have a better temporal resolution and signal to noise ratio.

For guided waves, numerical study enables to identify the Lamb 4 mode which is sensitive to the remaining steel thickness. First feasibility tests were performed on concrete plate to measure the A2 mode and the results demonstrate that this mode can be measured.

These first results obtained from these two methods are promising and complementary for the inspection of concrete/steel/concrete pipes on site.



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