Guided Waves for the monitoring of pipeline zones under composite repairs: from comprehensive to pre-deployment investigations

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Key words: Composite repairs, ultrasonic guided waves, Structural Health Monitoring, full-scale tubes, numerical and experimental investigations

Abstract
This paper deals with the health monitoring of pipes repaired locally with composite layers. It studies the feasibility of the use of the ultrasonic guided waves technique to monitor this kind of structures: 1/ detection of the occurring of a defect and 2/ surveying its growth. To this end, numerical and experimental investigations are carried out on full-scale tubes. Basing on these investigations, a methodology is developed to reach both aims.

1 INTRODUCTION
Composite repairs are attractive solutions to repair/reinforce cracked and / or corroded structures, such as pipelines [1]. The composite repair is wrapped around the metallic parent pipe (see an example given in Figure 1, extracted from reference [2]). “Use of composite wrap as an alternative to pipeline replacement can reduce safety risks, decrease pipeline downtime, save gas for sale, and decrease methane emissions to the atmosphere…” [3]. However, due mainly to thermo-mechanical fatigue and chemical reactions, the existing defects can grow, and/or new defects can occur in the pipe-wall, in the composite envelope or between them. Local nondestructive testing measurement such as the conventional ultrasonic testing can be used to monitor the growth of the initial defect(s) or the occurrence of another one (or some others). However, thought local techniques are precise due to the relatively high frequency with which they operate, they are too expensive. The alternative technique which offers the possibility to win time and save costs could be the ultrasonic guided waves (UGW). Indeed, UGW travel relatively through long distances without a drastic attenuation in several cases [4,5]. This technique should provide important information concerning the defect state. To do so, comprehensive investigations basing on analytical, numerical and experimental tasks were conducted. In the current paper, these investigations were followed by a pre-deployment study to rule on the technology readiness level of the proposed product/solution.

The paper consists of five sections. Section 2 concerns a brief description of the modeling investigations carried out to identify and optimize the main parameters that permit the health monitoring of this kind of structures using guided waves (ensuring the propagation for a relatively large distance with the best possible defect sensitivity). The section 3 is devoted to describe the achieved experiments and discuss the main obtained results. The section 4 deals
with conclusion and outlooks of the current study.

Figure 1: Examples of composite repair overlapping pipes [2]

2 MODELLING

Various modeling investigations were carried out. The predominant torsional mode T(0,1) is used due mainly to its lower sensitivity to surrounding media comparatively to the other guided wave modes.

The aim of these modeling studies is to identify and optimize as much as possible the parameters that can allow maximizing the distance of propagation for reasonable defect sensitivity. The main parameters studied here are:

i. Central frequency of excitation, and
ii. Material and Shape of the composite repair.

Briefly, it was shown that some frequencies are better than others, and altogether there is an alternation between “good” and “bad” frequency bands, where the transmitted energy, over the composite repair (i.e. in axial direction), is high and low respectively. This finding concords with previous results obtained on other kinds of structures (see [6,7] and [8] for example). Concerning the item ii, results revealed that the higher the extremity angles of the repair, the lower the energy of the transmitted wave over this repair (the angle $\phi$ in Figure 2). Figure 2 presents an example of the numerical simulations results obtained of this study in the frequency domain. Further details can be found in reference [9].

Figure 2: Not-scaled figure showing an example of a numerical result obtained in this study (axisymmetric wave propagation in frequency domain): from left to right, bare 6’’ steel tube, trapezoidal repair, and rectangular repair, respectively.
3 EXPERIMENTS

3.1. MOCKUPS MANUFACTURING AND MEASUREMENTS

Three steel tubes was supplied and installed. It was confirmed, after UGW measurements, that they are healthy. After that, an initial defect was created at each tube in order to mimic a real-world case. Scans to assess accurately the defects profile and dimensions were carried out by using a laser inspection system (see a typical result given in Figure 3 left). Then, these defects were filled with epoxy, and three composite repairs were deposited by Prokem company, as it can be seen in Figure 3 right.

![Figure 3: (Left) tridimensional laser scan of a region containing the machined defect, and (right), manufactured mockups: 6’’-steel tubes with composite repair with 3 different thicknesses](image)

Next, UGW measurements were carried out where pitch-catch as well as pulse-echo arrangement modes were adopted for first, assessing the attenuation in such structures, and second, monitoring the health of these structures (considered right now as healthy). It is worth noting that the first step of SHM protocol is the monitoring of a structure for a given period while it is healthy (or supposed to be), and this step is fundamental. This allows obtaining a reliable baseline database. Indeed, data acquisitions are always impacted by the environmental and operational conditions variations EOC (i. e. temperature, pressure, humidity, boundary conditions, etc.)[10]. If this item is not taken into account, it is probable to undergo false-calls. Consequently, database should be built with an enough number of signals acquired in various EOCs. Figure 4 presents a schematic showing typical experimental acquired waveforms and an illustration of the building of a database (left), and a cartography gathering a set of signals acquired during few months (right).

![Figure 4: Schematic showing typical experimental acquired waveform and illustration of the building of a database (left), and a cartography gathering a set of signals acquired during few months (abscissa axis = monitoring time or data)](image)
3.2. DEFECTS INITIATION AND GROWTH, AND THEIR DETECTIONS

After building the baseline database, two different kinds of defects are studied in the following chronology order:

i. defect simulating an abrasion, which could also simulate a disbonding defect (external defect), and

ii. defect simulating an inner corrosion

Both defects are created and then increased in different steps: 3 for the abrasion and 5 for the corrosion like-defect. Concerning the later, endoscopy testing is called for sizing the defect at each step and assess its shape. Results of endoscopy testing are to be correlated with UGW testing. The figure below shows a schematic of the defects and a result example obtained via an endoscope.

Figure 5: A schematic of the defects locations (left) and a result example obtained via endoscopy testing showing the dimensions and the shape of the machined defect (right). The color bar indicates the depth of the defect with regard to the inner surface the tube

As a reminder, the aim of this work is to verify if guided waves technique is able to detect this kind of defects, and if it is able to follow its growth.

Figure 6 (right) shows a typical result among those obtained. As it can be seen, the defect was detected successfully in its different steps. Concerning the classification of the created defect, the chosen damage index in this study shows that defect step 2 is bigger than defect step 1. In contrast, damage index of defect step 3 is lower than that of defect step 2. This is an ordinary phenomenon in guided waves because when the incident wave interacts with a defect, some constructive and destructive interferences occur, and this is closely dependent of the wavelength evolution with regard to the dimensions of the defect. Hence, for a given frequency (i.e. wavelengths), the signal amplitude increases with the defect until a given growth; after that, the signal amplitude decreases, then increases and so on. Alternated ascendant and descendant bands can be seen in Figure 6 (left). Further information concerning the phenomenon described here can be found in references [11] and [12].

The collected data during these experiments consist of 30 readings (5 * 5 defect steps + 5 baselines). As described previously, each acquisition is achieved at 5 central frequencies. So, in total, the collected data consist of 150 signals.
Figure 6: In the left-hand side, detection of a defect simulating an abrasion. Ds = Defect step. In the right-hand side, oscillator variation of reflection coefficient for a given frequency (l is the wavelength. When the defect axial length is equal to l/4 or 3/4, the reflection coefficient reaches its maximum).

The 150 signals obtained were processed then by using a code developed at Institut de Soudure. A typical result for a given frequency is shown below in Figure 7, which represents damage index versus the steps of defect growth (at each defect step, 5 signals were collected; vertical dashed lines delimit the data corresponding to defect steps growth). As it can be discernibly seen, the defect is detected and guided waves monitoring technique was very sensitive to its growth.

Figure 7: Damage index versus damage growth for a given frequency. Ds = defect step. Vertical green dashed lines separate these defect steps. 5 measurements were collected for each Ds to check reproducibility. Horizontal dashed red lines are the mean of the 5 damages extracted from these measurements.
The figure below shows the created defect at its last step (the fifth one). As it can be remarked, by comparison with 1 € piece, the defect is small.

![Image of machined internal defect](image)

Figure 8: the machined internal defect at its last step (the fifth one). The 1€ piece is shown to give an idea about the size and the shape of the defect.

4 CONCLUSIONS

The current paper concerned the monitoring feasibility of pipeline composite reparation of tubes using ultrasonic guided waves technique. Numerical and experimental investigations on full-scale tubes have been carried out. The main results are the following:

- composite repaired pipes are high attenuating media. Attenuation is closely related to frequency,
- in testing context, defect is not detectable,
- detection of relatively small like-corrosion defect whatever its place (inner or outer), is ensured in monitoring context,
- detection of defects like-corrosion growth is ensured in monitoring context,

It has to be noted that the present paper recapitulates a part from a deep study. For the sake of brevity, the rest of this study is not included here. The main other conclusions have the merit to be given here as a complement of the aforementioned conclusions:

- the stability of the monitoring system is satisfactory. An experimental result was compared with literature, and showed better stability,
- the statistical algorithm implemented to overcome the variability in the database is efficient.

Basing on the outputs of this study, it was decided to implement an evaluation tool on a pilot site.

ACKNOWLEDGEMENT

The authors are grateful to Total for cofunding this study, and Association Nationale de Recherche et Technologie (ANRT) for the partly financial support (i.e. CIFRE) of Mahjoub EL Mountassir’s PhD.
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