Ultrasonic Inspection of Adhesive Joints of Composite Pipelines

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Abstract. Composite pipelines are an attractive solution when traditional materials are not suitable for this purpose, which happens frequently at aggressive environments and also where the structural weight is a limiting factor. This work studies the application of the ultrasonic technique at the detection of defects as lack of adhesive and lack of adhesion, commonly found in adhesive joints of glass fiber reinforced plastic (GFRP) pipelines applied at onshore and offshore facilities. Computational simulations were conducted in CIVA 11© software (beta version) in order to obtain the best possible configuration for the inspections, applying the pulse-echo technique. Experimental results were compared to these simulations and several transducers were tested. An inspection methodology and reference blocks were developed for the calibration of the inspections. Some samples were selected for cutting in order to compare the ultrasonic results and the real condition of the joints. Results show that smaller frequencies are suitable for the inspection of this material and focused probes present more accurate results.

Keywords:

INTRODUCTION

Composite materials can be frequently found in several sectors of the industry since they present high mechanic resistance, low specific weight and high corrosion resistance. Thus, it is often possible to find these materials in critical structures, subjected to static or dynamic efforts, whose operation should be continuous and catastrophic structural failure and is therefore inadmissible. Consequently, such structures should be periodically inspected to ensure their integrity. Several non-destructive techniques are already consolidated on the inspection of metallic materials, which are traditionally used under these conditions. However, many of these techniques are inefficient in the detection of defects in composite structures. Thus, the applicability of non-destructive testing inspection of composite materials has been studied in recent decades.

Several authors in the literature have already investigated the application of the ultrasonic technique in fiber reinforced plastics (FRP). Delaminations, voids, porosity, cracks, inclusions and areas poor and rich in resin are defects that were already successfully detected by conventional ultrasound in this type of material [1-3], but most works developed in this field are limited to the detection of the loss of adhesion between matrix and reinforcement, fatigue and low energy impact damages, which demonstrates the necessity of further research [2].

Since FRPs present a high anisotropy, the ultrasonic wave energy is highly attenuated when travelling inside these materials. Consequently, several authors [4-7] studied the ultrasonic technique in FRPs when it is applied in thin structures. In this work, thicker GFRP pipelines are studied, which brings a great challenge for the application of the ultrasonic technique in this material.

SIMULATIONS IN CIVA

Before carrying out the inspections, simulations were conducted in the Ultrasonic Module of CIVA 11 (beta version) software in order to verify the feasibility of the application of the ultrasonic inspection in this material.

CIVA is a NDT simulation platform in which the ultrasonic module relies on the "pencil method" approach to compute beam propagation and the interaction with defects is calculated using either “Kirchhoff” approximation or the Geometrical Theory of Diffraction “GTD”. Version 11 of CIVA brings a major improvement compared to previous ones regarding the possibility of computation of the specimen specular interface echos, making it possible for the user to evaluate the ultrasonic response of interior interfaces of complex geometries.

This improvement allowed the use of CIVA in this work since the studied specimens are constituted of three main layers: two GFRP pipelines bonded by an adhesive layer. This structure was virtually reproduced in a CAD specimen and imported in CIVA as a 3D heterogeneous CAD, as shown in Fig. 1. Then, the ultrasonic response of this specimen was evaluated under several circumstances, as will be discussed in the upcoming sections of this paper.

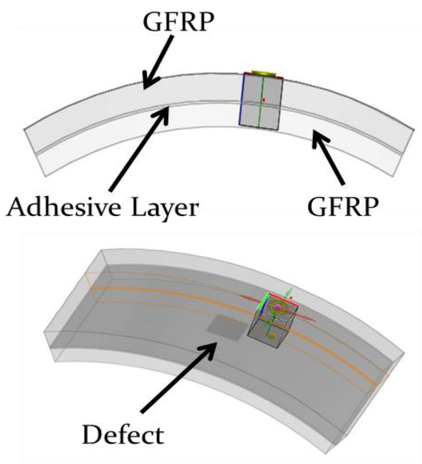
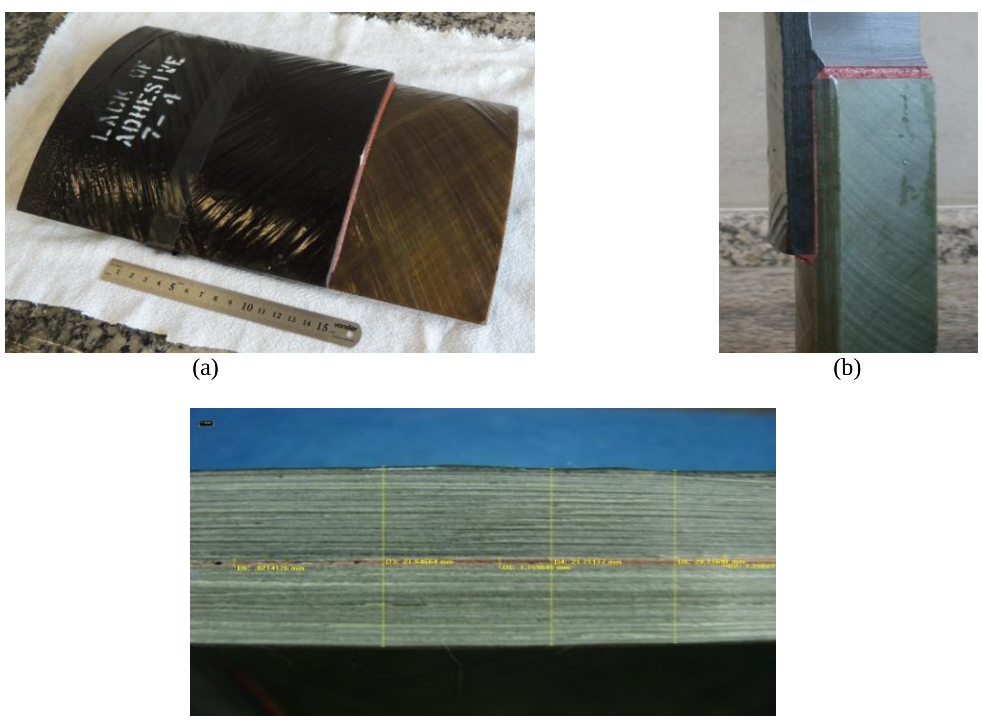


FIGURE 1. 3D CAD specimen applied in CIVA for the performed simulations.

EXPERIMENTAL

Thirty samples that were part of a 16” diameter pipeline joint, which is composed by an epoxy matrix reinforced by glass fibers, were used for this study. The adhesive layer that connects the parts is an epoxy resin (Fig. 2). Typical

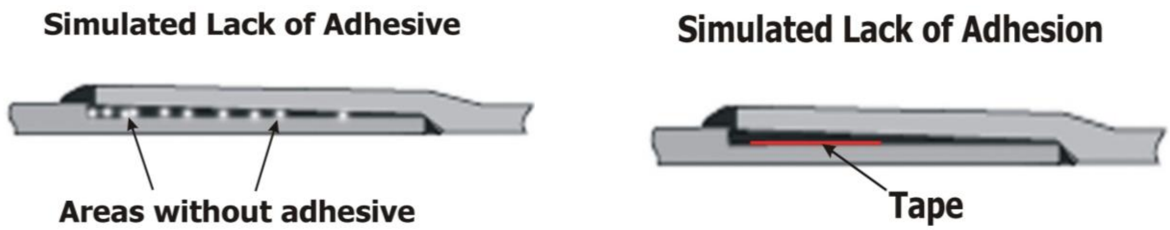


(a) (b)

(c)

FIGURE 2. Image of the studied samples: (a) Section of a 16" diameter pipe, (b) Cross section of the overlapping and (c) Overlapping in detail.

defects presented by this type of material are the lack of adhesive and the lack of adhesion between the adhesive layer and the pipe's internal surface. Lack of adhesive is simply the absence of the adhesive layer at some regions of the joints, and this defect was simulated by inserting a smaller amount of adhesive than the indicated by the manufacture for the proper union of the joint. Lack of adhesion is a more complex defect because even though the adhesive layer is present, it is not properly bonded with the pipe's internal surface, what could lead the pipeline to catastrophic failure. This defect was simulated by inserting a polymeric tape of 200μm thickness between the adhesive layer and the pipe's surface. Both defects are illustrated in Fig. 3.



(a) (b)

FIGURE 3. Studied defects: (a) Lack of Adhesive simulated defect and (b) Lack of Adhesion simulated defect.

The detectability of the defects and the frequency behavior of the ultrasonic waves were both explored at the simulations in CIVA 11. The joints were virtually reproduced and imported in CIVA 11 as 3D heterogeneous CADs. The defects were simulated as an air layer of 1mm thick, in the case of the lack of adhesive, and an acetate layer of 0.2mm thick, in the case of the lack of adhesion defect, as shown in Fig. 1. Inspections with commercially available single element transducers with the frequencies of 1.6MHz, 2.25MHz and 5MHz were then simulated in the pulse-echo contact mode.

The experimental procedure applied the pulse echo configuration using those same transducers frequencies. The flaw detector was a General Electrics USIP 40, as shown in Fig. 4. Calibration blocks which reproduce the structure of a well bonded joint were developed in order to enable the calibration of the sensitivity of the inspections. The scanning of all specimens was carried out at a non-continuous scan since the surface and the superficial irregularities jeopardize the coupling.

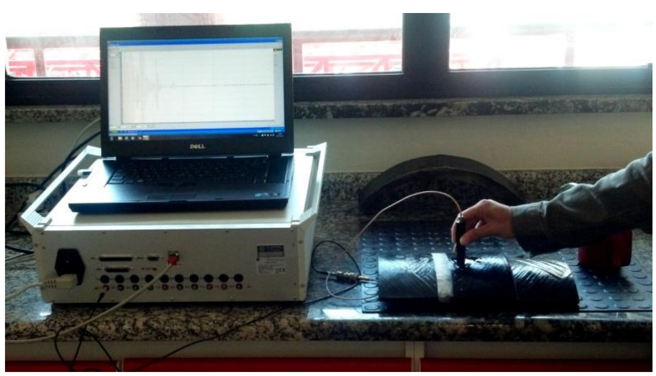
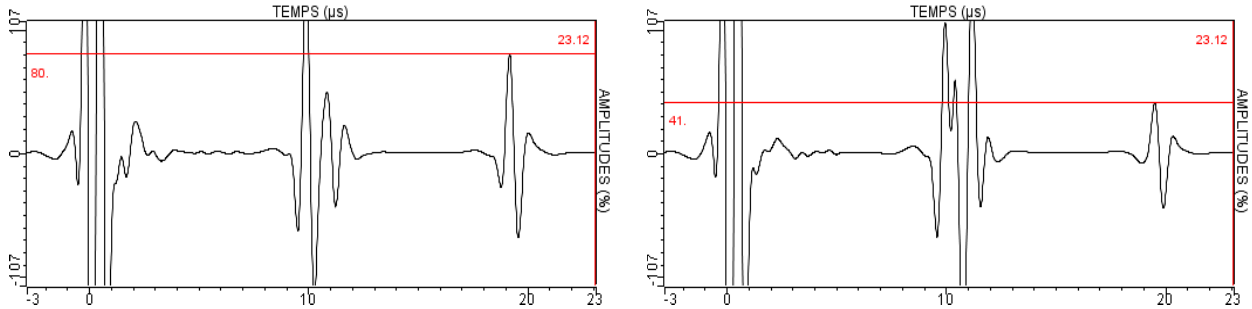


FIGURE 4. Ultrasonic pulse-echo apparatus.

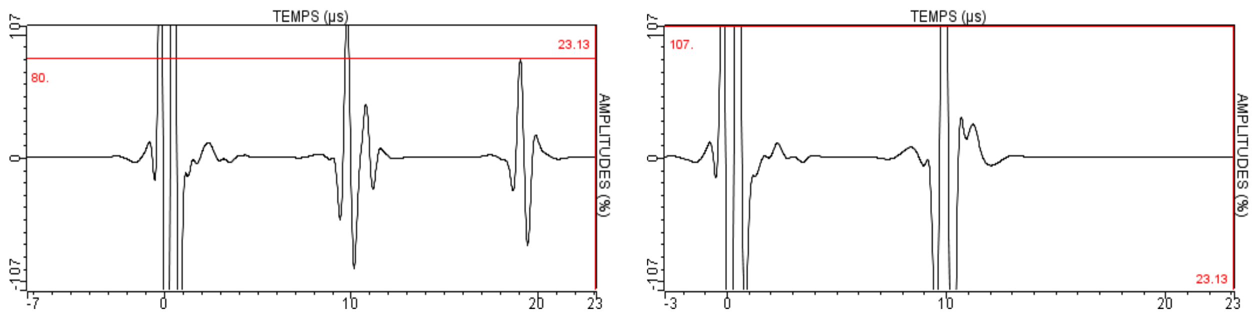
RESULTS AND DISCUSSION

The results from the simulations in CIVA 11 are here represented as A-scans in Figs. 5 through 7. Figure 5 presents the A-scans obtained for the specimen with lack of adhesion with the frequency of 1.6MHz. It can be seen that when the transducer is over a well bonded area of the joint, the A-scan has three distinguishable echos: the first one from the surface, the second one from the adhesive layer and the third one from the backwall. When the transducer is over a defective area, the third echo, *e.g.*, the backwall echo, is highly attenuated, proving that there is something in the specimen structure preventing the sound beam to reach the joint's internal surface. This same behavior was found for the lack of adhesive defect, as can be seen in Fig. 6.



(a) (b)

FIGURE 5. A-scans produced by CIVA for the frequency of 1.6MHz: (a) Signal from a non defective area and (b) Signal from an area with lack of adhesion, with the rise of amplitude of the second echo (adhesive layer echo) and the third echo (backwall echo) attenuated.



(a) (b)

FIGURE 6. A-scans produced by CIVA for the frequency of 1.6MHz: (a) Signal from a non defective area and (b) Signal from an area with lack of adhesive, with the rise of amplitude of the second echo (adhesive layer echo) and the inexistence of the third echo (backwall echo).

The simulations shown in Figs. 5 and 6 demonstrate that the pulse-echo technique is suitable to detect both types of studied defects. Furthermore, the frequency behavior in this material was also evaluated in order to obtain the best configuration for the experimental procedure. This was achieved by simulating inspections in both specimens using the same parameters but one: the transducer. The following frequencies were tested: 1.6MHz, 2.25MHz and 5MHz. Figure 7 shows the superimposition of three A-scans of a non-defective area, each one from one of these frequencies. It can be seen from this A-scan that the 1.6MHz transducer presents the best signal to noise ratio among the ones tested. It also can be seen that the backwall signals from higher frequencies have low amplitudes in a non defective area, making it difficult the distinction between well bonded and defective areas. These results indicate that smaller frequencies, as the 1.6MHz applied, are best suitable for the inspection of this material.

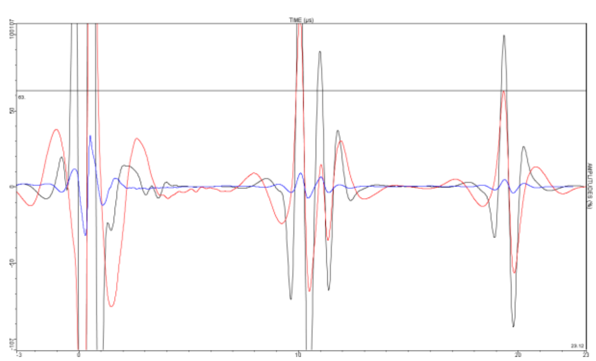
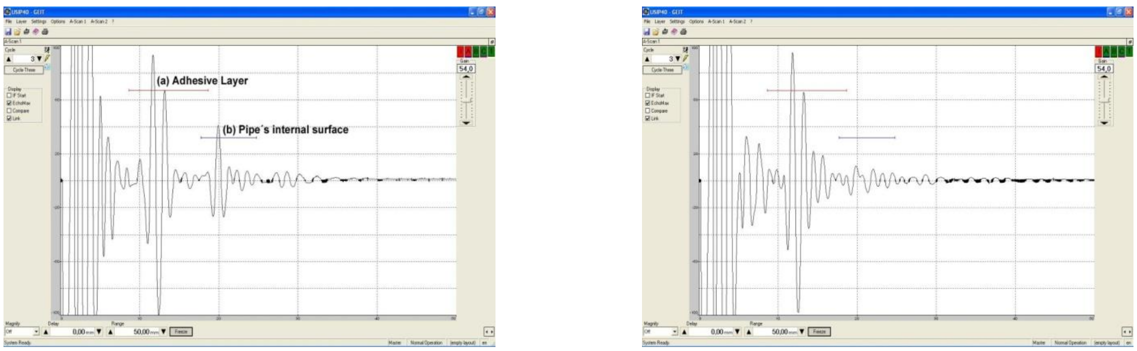


FIGURE 7. Superimposition of three A-scans: in black, the A-scan from the 1.6MHz transducer; in red, the A-scan from the

2.25MHz transducer; in blue, the A-scan from the 5MHz transducer.

These same three frequencies were also evaluated in the experimental procedure, and the same behavior was observed. Therefore, all results presented in this paper were produced with the 1.6MHz transducer.

Figure 8 presents two A-scans obtained with the 1.6MHz transducer. Figure 8(a), taken in a well bonded area, shows two clear signals: the first one is from the adhesive layer and the second one is from the pipe's internal surface. However, when a defective area is scanned, the wave is partially or completely attenuated while passing by the adhesive layer and the internal surface signal is almost impossible to be seen (Fig. 8(b)).



(a) (b)

FIGURE 8. Pulse-echo A-scans: (a) non defective area and (b) defective area

The inspection gain was obtained from the reference block developed for the proposed experimental procedure. A signal taken from this block is adjusted, using the gain control of the equipment, in order to elevate the backwall signal of this block to 80% of the screen, as shown in Fig. 9. This gain is used as the inspection gain.

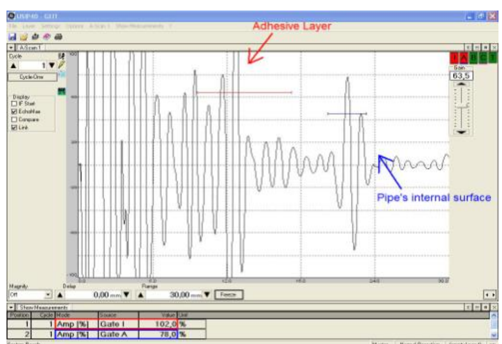
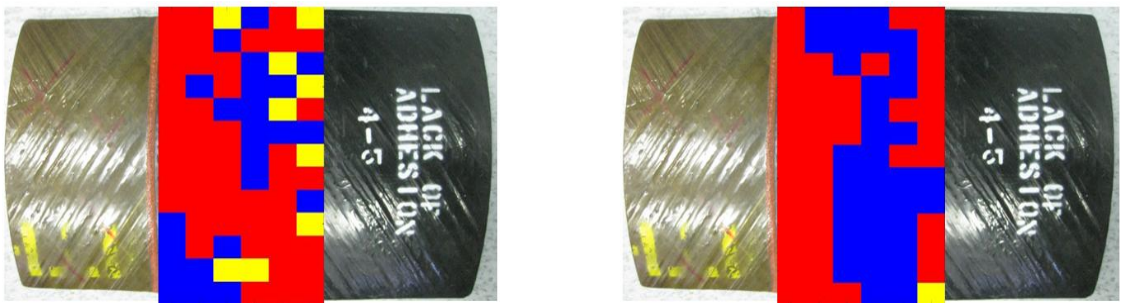


FIGURE 9. A-scan taken from the reference block, with the backwall echo adjusted to 80% of the screen

The integrity of the joints was evaluated by monitoring the amplitude of the backwall echo of the A-scans. In the adopted acceptance criteria, amplitude values related to the backwall lower than 35% of the screen were considered defective regions; values between 35 and 40% were considered "transition" regions, or may or may not contain defects and require more careful analysis, and amplitudes above 40% were considered as non-defective regions. From these values, it was possible to generate C-scan maps in order to locate and size the defective regions. Figures 10 and 11 show some examples of the obtained C-scans. In these C-scans, the gray colored areas correspond to a low amplitude signal and possibly, defective regions. The lighter colored regions were considered transition areas that are not yet possible to define as defective or not. The darker areas were considered well bonded ones.

(a) (b)

FIGURE 10. C-scans from specimens with lack of adhesion: (a) Lack of Adhesion 4-2 and (b) Lack of Adhesion 4-3

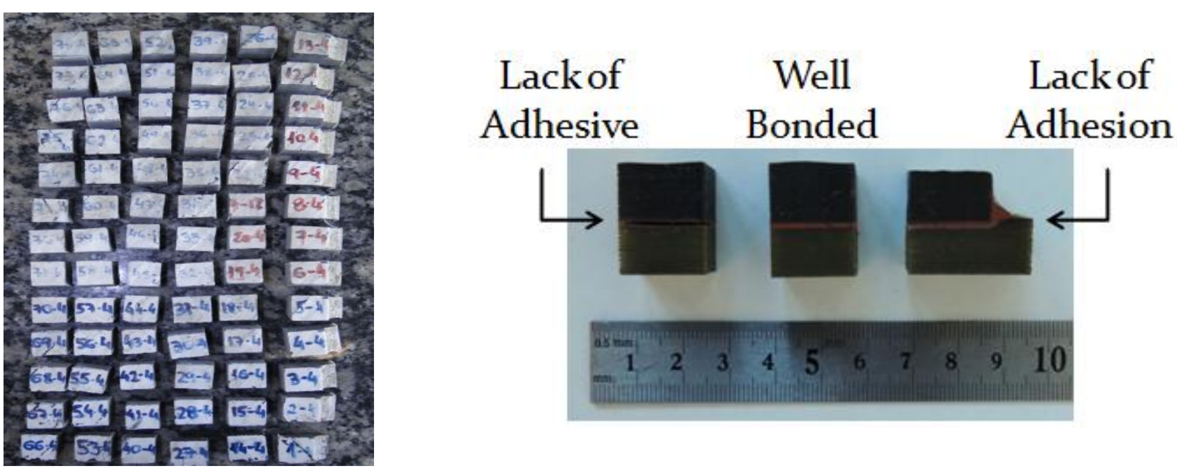


(a) (b)

FIGURE 11. C-scans from specimens with lack of adhesive: (a) Lack of Adhesive 8-2 and (b) Lack of Adhesive 8-3

In order to evaluate the technique and the adopted acceptance criteria, some specimens were cut after the ultrasonic inspection and the real state of the adhesive layer of the joints was obtained. Figure 12 demonstrates the aspect of one specimen after the cut and some particular sections are also shown in detail.

From these cuts, it was possible to assemble C-Scan maps related to the real state of the joints and the comparison with the ultrasonic results could be made, as shown in Fig. 13 for two specimens. This comparison showed that the accuracy of the proposed methodology regarding the real state of each point of inspection is always above 60% for all specimens, proving that the ultrasonic technique is suitable for the inspection of this material.



(a) (b)

FIGURE 12. Example of one of the specimens after cutting. (a) One whole sectioned joint and (b) examples of some of the obtained sections, presenting the simulated defects.

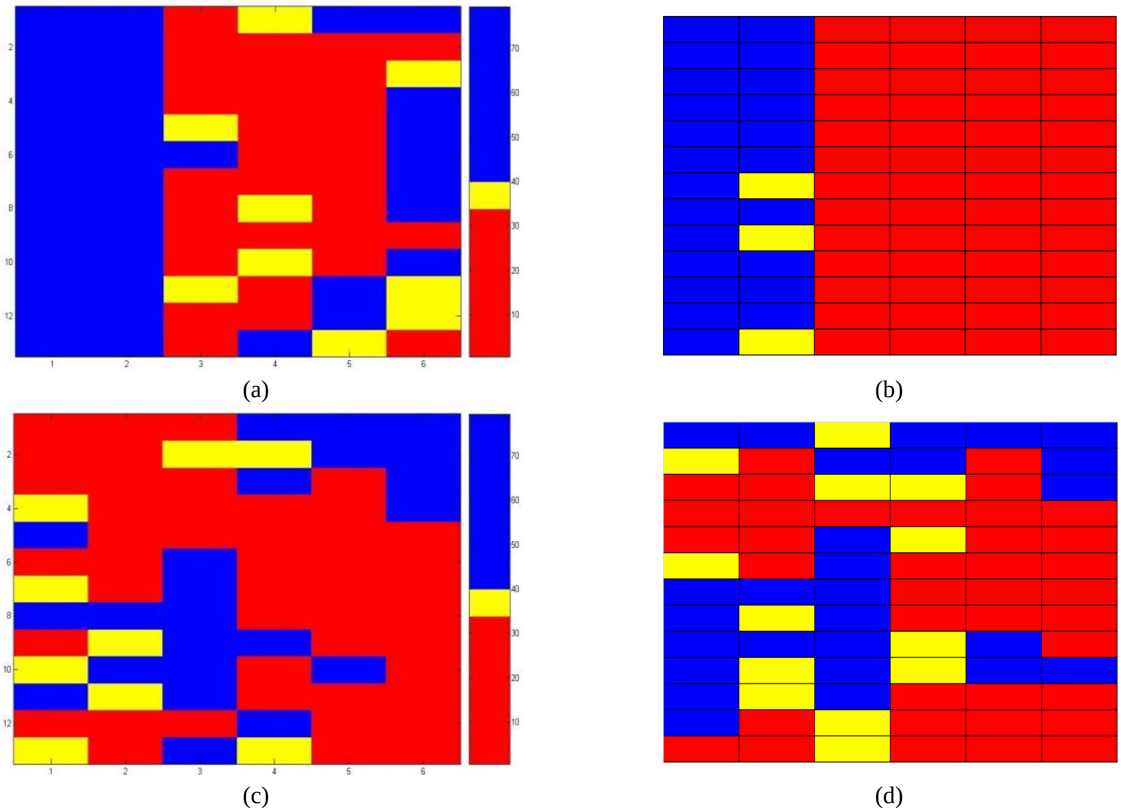


FIGURE 13. Comparison between ultrasonic C-scans and the real state of the joints. (a) Ultrasonic C-scan for the sample Lack of Adhesion 4-2, (b) Real state of the sample Lack of Adhesion 4-2, (a) Ultrasonic C-scan for the sample Lack of Adhesive 8-2, (b) Real state of the sample Lack of Adhesive 8-2

However, some limitations of the applied technique were found after this comparison. The surface irregularity and curvature of the samples are characteristics which prevent the proper coupling between the transducer and the pipe’s surface, thereafter preventing a continuous inspection with the pulse echo technique. Consequently, a more accurate sizing of defective areas can be compromised, since the signals are acquired punctually. A more accurate sizing can be achieved through the use of focused transducers and/or the automation of this inspection.

The feasibility of the application of focused transducers was evaluated through a new simulation in CIVA 11 with a 1MHz spherically focused transducer. The results are shown in Fig. 14, where it is possible to verify that this transducer presents the same behavior as the previous ones, being capable to distinguish between well bonded and defective areas.

CONCLUSIONS

The ultrasonic inspection, through the proposed methodology, was adequate for the detection of defects as "Lack of Adhesion" and "Lack of Adhesive", as well as the developed reference block, which also proved to be suitable for the calibration and validation of the inspections.

CIVA 11 was able to predict the ultrasonic response and the frequency behavior in the studied GFRP structure, showing the importance of the use of simulation tools on the investigation of the application of the ultrasonic inspection of complex geometries.

Transducers with frequencies around 1MHz showed the best behavior at the inspection of this material, presenting distinguishable signals between well bonded and defective areas, as well as a great signal to noise ratio, which indicates that this frequency is the most suitable for the inspection of this material.

The cut of some specimens allowed the examination of the real state of the joints and a comparison with the ultrasonic inspection could be performed. This showed that the ultrasonic inspection has an accuracy of over 60% of the cases and revealed a resolution problem, which may be overcome by the use of focused transducers.

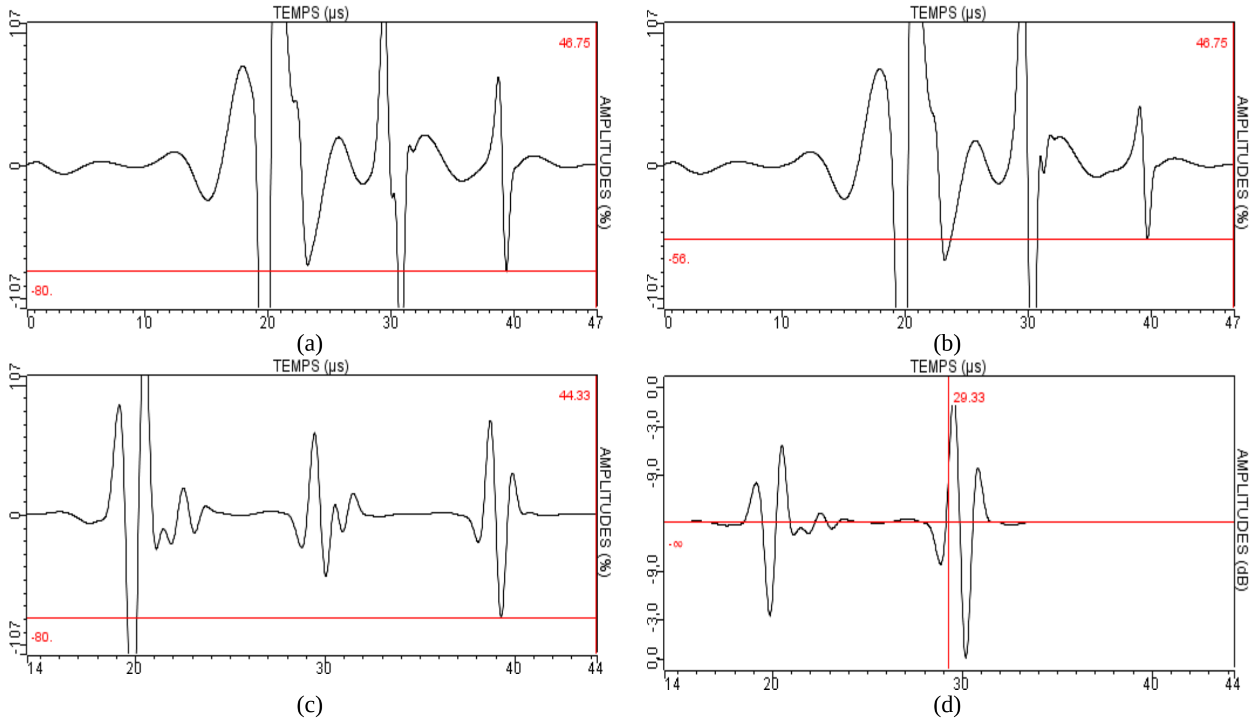


FIGURE 14. A-scans produced by CIVA for the 1MHz focused transducer: (a) Signal from a non defective area, (b) Signal from an area with lack of adhesion, with the rise of amplitude of the second echo (adhesive layer echo) and the third echo (backwall echo) attenuated. (c) Signal from a non defective area and (d) signal from an area with lack of adhesive, with the rise of amplitude of the second echo (adhesive layer echo) and the inexistence of the third echo (backwall echo).

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