Original Article

Phased array inspection of glass fiber reinforced polymers pipeline joints

Priscila Duarte de Almeida, Gabriela Ribeiro Pereira

A Nondestructive Testing, Corrosion and Welding Laboratory (LNDC), Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, RJ 21941.596, Brazil
b Materials and Metallurgical Engineering Department, Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

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Glass Fiber Reinforced Polymers (GFRP) laminated joints combine properties such as high mechanical resistance, low specific weight and high corrosion resistance, features that allow their application in harsh environments. The structural integrity of these components must be ensured; therefore, their inspection through non-destructive methods capable of certifying such integrity is necessary. This work evaluates the phased array inspection of GFRP laminated joints, in order to detect defects frequently found in this material. For the development of the study, artificial flaws representing interply delamination were inserted in the material. The experiments were conducted with a 32 elements matrix probe (500 kHz frequency). Two focal laws were applied aiming the detection of the existing defects. Results indicated that the proposed methodology is adequate for the detection of the flaws, highlighting the performance of focal laws with focal spots in the back wall of the joint.

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1. Introduction

Fiber Reinforced Polymers (FRP) present properties as low specific weight and high mechanical and corrosion resistance, a combination which promotes this material as an interesting choice for its application in facilities that run under harsh environments. They are commonly found along the oil and gas production line and there is a great concern on the development of non-destructive techniques (NDTs) capable of assessing their integrity [1,2].

Among all available NDTs, the ultrasonic/phased array (UT/PA) inspection are two of the most widely applied techniques on the evaluation and characterization of metallic pipelines since they are knowingly able to detect critical defects which may arise in these components. Additionally, several authors have already proved their efficiency on the detection of delamination [3], debonding [4], porosity [5], wrinkles [6] and several other defects that might be present in composite structures. However, apart from the consensus that lower frequencies are best suitable for the inspection of FRP [2,4,6,8,10], literature still fails to present a standard methodology for the application of UT/PA on composite materials. The major challenge to their application on FRP lies on the structure of this material. The intrinsic anisotropy and heterogeneity of composite materials combined with the high
absorption power that polymers promote on the propagation of ultrasonic waves, result in a great loss of energy through scattering, skewing and absorption, especially on components that have thicker sections [2,7,8].

The benefits from a multielement inspection provides PA as a more versatile technique than UT in terms of beam forming and data imaging/registering. Therefore, its application on challenging materials becomes interesting, once the user is able to shape and process the signal according to the experimental scenario. Some advanced approaches have been successfully tested on composites recently. The Surface Adaptive Ultrasound [9], in which the incident PA beam is recalculated based on the surface profile of the part, optimizes the beam propagation inside the material. The Full Matrix Capture [10] combined with a post-processing algorithm such as the Total Focusing Method [10] or the Plane Wave Imaging [11], creates highly focused images which might show defects not detected through standard inspections.

In this context, this work aims the detection and location of defects frequently found in GFRP joints through the phased array inspection. For the development of the study, artificial flaws representing interply delamination were inserted in the material for further inspection by phased array. The experiments were carried out with a 32 elements matrix probe (500 kHz frequency) and a 64 parallel channels equipment. Two focal laws were applied and parameters such as angular sweep and focalization were evaluated.

2. Materials and methods

Two GFRP laminated joints were evaluated, as presented in Fig. 1. The pipelines were manufactured through the filament winding process (±55°), consisting on an epoxy matrix reinforced with glass fiber. Their nominal diameter and thickness were 101.6 mm and 7 mm, respectively. The union was assembled through the hand lay-up process, with the application of 7 glass fiber layers, (2 woven rovings and 5 mats), impregnated with an epoxy resin. The total thickness of the unions once the laminate process was finished varied from 17 mm to 37 mm.

The first sample was fabricated as indicated by the manufacturer. On the second sample, artificial delaminations consisting of 0.1 mm thick acetate sheets were embedded between each layer during the lamination process, with a total of 6 inserted flaws. These flaws had a rectangular morphology varying from $15 \times 40 \text{ mm}^2$ to $15 \times 80 \text{ mm}^2$.

A 32 elements matrix probe (6 mm pitch) was used for the PA inspections. The frequency was 500 kHz and the scanings were made under water immersion. Two focal laws were used: Single Point Focusing (SPF), with the focal point established at the pipe inner diameter (ID) and Dynamic Depth Focusing (DDF), with several focal points through the material thickness.

The samples were also inspected with a second non-destructive technique, Computer Tomography, in order to corroborate the PA results. The GE Brightspeed 16 detector was used with a resolution of $0.65 \times 0.5 \times 0.5 \text{ mm}^3$ (depth × width × length).

3. Results

Areas free of flaws show results similar to the ones presented on Fig. 2(a), in which a single line B-scan is presented and the cross section of the material can be seen, revealing the profile of the union. The PA signal in this case has low amplitude through the whole thickness of the material (blue and green colors) and the pipe’s back wall signal is visible through all the

Fig. 1 – Inspected samples.

Fig. 2 – B-scans of (a) area free of flaws and (b) defective area.
Fig. 3 - Results from sample 1: (a) C-scan maps for both focal laws, (b) B-scan map showing high amplitude signals on the OD and (c) ID.

Fig. 4 - Results from Sample 2 with the SPF focal law. (a) Comparison between the projected and experimental C-scans. (b) and (c) B-scans showing unexpected flaws.

scan line. Fig. 2(b) presents a single line B-scan from a defective area. In this case, the existence of the flaw prevents the sound wave to reach the inner diameter of the pipe. Consequently, a high amplitude signal (red color) is generated in the volume of the material, which is followed by a total loss of the back wall signal.

3.1. Sample 1

Fig. 3(a) presents the results from sample 1, which did not have any artificial flaws inserted. In this image, planified C-scans obtained with both focal laws are shown. In order to simplify the results interpretation, the signal amplitudes were divided
into 3 categories: low amplitude (green), medium amplitude (yellow) and high amplitude (red). As expected, Sample 1 was mostly indicated as free of flaws (low amplitude signals) by both focal laws. However, SPF results showed an unexpected area with a high amplitude signal. Further evaluation of that area showed that these signals are from two particular locations:

- Near outer diameter (OD), which might be small bubbles left on the surface, generated during the final stages of lamination (Fig. 3b);
- Near inner diameter (ID) of the pipe, which might be unknown flaws existent in the pipes prior to the union assembly (Fig. 3c).

3.2. Sample 2

Fig. 4(a) presents the C-scan results from the SPF focal law on the inspection of sample 2, which had six artificial flaws inserted. This result is compared to the expected C-scan regarding the position on which the flaws were placed. All 6 flaws were detected and can be related to their expected position (Fig. 4a). Additionally, this focal law also detected two unexpected defects, which are highlighted in gray on the C-scan. Fig. 4(b) and (c) present the B-scans of the unexpected flaws in detail.

Fig. 5(a) presents the C-scan results from the DDF focal law on the inspection of sample 2. Five out of the six flaws were detected and can be related to their expected position, as shown on Fig. 5(a). Once again, an unexpected defective area was detected, which is highlighted in gray on the DDF C-scan and shown in detail on the B-scan presented on Fig. 5(b).

4. Discussion

Both focal laws presented similar results on the inspection of samples 1 and 2. Considering only sample 2, five out of the six artificial defects were detected by all the scans. Flaw 6, the one closest to the outer surface, was only partially detected by the SPF focal law. However, on both scans, the overall response of this defect was a medium amplitude signal, as can be observed on Figs. 4(a) and 5(a). The depth of this flaw, considering the number of layers that were added above, suggests it would be the easiest one to detect, a fact that was not observed experimentally. It is believed that there was a good adhesion between the epoxy resin and the embedded flaw, preventing the PA inspection to detect this defect.

It is visible on the B-scans how the profile of the samples change along the perimeter of the pipe. Fig. 3(b) and (c), for example, are B-scans from different circumferential positions of sample 1; the change in the material thickness is clearly
visible when a comparison between both images is made. This behavior, however, did not seem to influence the PA results on the inspected samples, showing that the technique is able to overcome thicknesses irregularities on this material.

Sample 2 had an unintentional defect detected by both focal laws. This defect was clearly identified on the B-scan images and was located at the same region on both scans, even though the SPF scan determined a larger defective area when compared to the DDF one. A second non-destructive technique, Computed Tomography (CT), was used to verify the existence of this defect. The CT inspection showed that there is indeed a flaw in this position (Fig. 6), which is a debonding between the pipe surface and the first laminated layer.

CT also showed the existence of the unexpected OD and ID flaws detected by the PA inspection, as presented on Fig. 7. They were observed on both samples, and the SPF focal law was more sensitive to them than the DDF. This is possibly because these focal laws were not corrected for the anisotropy of the material, which has a greater influence over DDF than SPF. As the DDF focal law is focused on several points of the material, it requires a more complex calculation for the elements delay. Therefore, the influence of applying an isotropic focal law on the inspection of an anisotropic material cannot be neglected. As a result, DDF had a lower performance on the detection of smaller and deeper indications when compared to SPF. Thus, even though both focal laws are already suitable for the detection of the investigated flaws, the results can still be improved for an accurate sizing and detection of other types of defects.

5. Conclusions

This work investigated the phased array technique on the inspection of GFRP laminated joints with maximum thicknesses of 30 mm. Artificial delaminations were evaluated and all flaws were detected, indicating that the technique is suitable for the inspection of this material.

Unintended flaws were also detected by phased array and their existence was confirmed with results obtained from computed tomography scanning.

The anisotropy of the material played an important role on the results obtained from different focal laws. Even though detection of the expected flaws was not greatly influenced, the correction of the focal laws for the anisotropy is indicated for an accurate sizing and detection of other types of defects.

Conflicts of interest

The authors declare no conflicts of interest.

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