APPLICATIONS AND ADVANCES OF THE ACTIVE THERMOGRAPHY FOR THE INSPECTION OF COMPOSITE MATERIALS USED IN INDUSTRY

Marcella Grosso [(1)], Sergio D. Soares [(2)], Isabel C. P. Margarit-Mattos and Gabriela R. Pereira [(1)]

(1) Laboratory of Non Destrutive Testing, Corrosion and Welding (LNDC), Department of Metallurgical and Materials Engineering, Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

(2) Petrobras Research Center (CENPES), Rio de Janeiro, Brazil

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Abstract

In this paper, the ability of the active thermography technique (Pulsed, Pulsed Phase and Lockin) was evaluated for the inspection of structures made of composite materials that are used in the petroleum and petrochemical industry. Two types of GFRP joints (adhesive-bonded and laminated) and one sample with anticorrosive composite coating were studied, with controlled defects being inserted to evaluate the capacity of the technique for the defect detection. In addition, a computational simulation model was developed to optimize the results obtained experimentally and also be a tool to estimate the limit of detection of the technique in these materials. According to the results obtained, the use of the Active Thermography technique for the inspection of these composite materials showed the potential of the technique for detection of defects that are common to occur in these materials and are not detectable by visual inspection. The computational simulation model created proved to be reliable and useful for the reproduction of the physical phenomena involved in the experiments and thus becomes an important complementary tool to optimize the results to be obtained in the inspection of these materials.

1. INTRODUCTION

The critical structures made of composite materials, particularly in the petrochemical industry, have been continuously employed often on platforms, especially in pipes for water or oil transportation, and in industrial plants, such as anticorrosive composite coatings for storage tanks and heat exchangers. However, the integrity of these materials is compromised by the presence of defects, which can lead to risks of failure and severe damages to the environment. Therefore, the application of nondestructive techniques becomes very important for detecting, locating, sizing defective regions during the manufacturing, installation and service life of composite materials.

Among the nondestructive techniques, thermography has been considered a powerful technique for the inspection of composite materials due to its main advantages: no contact with the surface, fast inspection, easy interpretation of thermograms and successfully used in the inspection of high emissivity materials, such as composite materials. The thermographic technique consists of analyzing the temperature distribution on the surface of the material (illustrated in the form of thermograms). The presence of subsurface defects in the inspected materials alters both the diffusion rate and the heat flow, so, in the thermograms obtained from the inspection by an infrared camera, these defects appears as areas of different in relation to the rest of the material (where there is no presence of defects). This is the principal mechanism to detect defective regions in thermograms obtained by thermography [1-4].

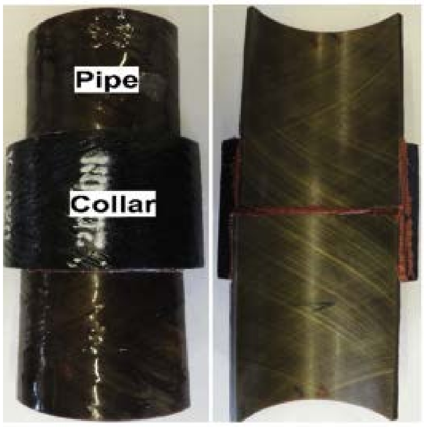
According to the thermal pulse type ad data analysis method, the active thermography can be classified as: Pulsed, Pulsed Phase, Lockin, Step Heating, Pulsed Eddy Current Thermography and Vibrothermography. For the present paper, Pulsed, Phase Pulsed and Lockin modalities will be evaluated. The Pulsed Thermography consists of briefly heating the sample surface and, then, the surface temperature decay is recorded. The result of the inspection using this modality is presented as a sequence of thermograms. In Pulsed Phase Thermography, the temperature evolution over time obtained in Pulsed modality is converted to the frequency domain through the Fourier Transform (FFT) and the result is expressed in two images, one referring to the values of angle of phase and the other concerning the amplitude (Fourier module) for each pixel at the chosen frequency analysis. The Lockin mode consists of the periodic heating of the surface of the material through modulated lamps and simultaneously the temperature evolution is monitored along the heating cycles. For each test, it is necessary to choose a single frequency of modulation and the choice of this is depends on the depth of penetration of the thermal wave desired in the material. The result of the Lockin modality is presented in the form of two images, one referring to the phase angle and the other referring to the amplitude, both generated by Fourier transform [1,5,6].

The use of computational simulation model associated with non destructive techniques has become an increasingly present task both in research and in industry. These tools allow the study of the best configuration of parameters to be used in inspection (experimental procedure), thus optimizing the results, both from the point of view of time and resources and also brings the knowledge of the limits of detection of the technique. In this paper, we will present the creation of a computational simulation model through finite elements for numerical reproduction of the physical phenomena present in the pulsed active thermography test and the preliminary results already obtained with the samples of the study experiments after the validation of the model.

In this paper, the ability of Active Thermography will be evaluated for the inspection of two types of GFRP (Glass Fiber Reinforced Polymer) joints (adhesive-bonded and laminated) used in pipelines and for inspection of some types of composite coatings that are used in storage tanks. Both experimental and simulation studies will be developed in order to evaluate the technique on the detection of defects that are found in these structures.

2. MATERIALS AND METHODS

The first sample (S1) used in this study is a concentric adhesive bonded joint of GFRP. The sample is formed by two pipes, with a diameter of 101.6 mm, thickness of 5 mm, joined trough a collar of 12 mm thickness. An epoxy adhesive, with a thickness of 1 mm, was applied both over the collar’s inner surface and over a surface of the pipes which was introduced into the collar. On the adhesive layer, two defects of lack of adhesive were inserted. Figure 1 shows a representative scheme of the geometry and positioning of the defects inserted in the adhesive layer.



(a) (b)

Figure 1 – Photography of the ashesive joint (sample 1) viewed from: (a) outside and (b) inside [7].

The second sample (S2) evaluated in this study is a laminated joint of GFRP. This sample consists of two pipes, with a diameter of 152.4 mm, produced by filament winding and joined by the application of successive composite layers on the surface of the pipes, through a lamination process. The thickness of the joint varies from 10 to 25 mm. During the assembly of the joints, artificial defects were inserted between the composite layers and on the pipe surface to simulate, respectively, delamination and debonding defects. Figure 2 shows a photograph of the laminated joint sample.

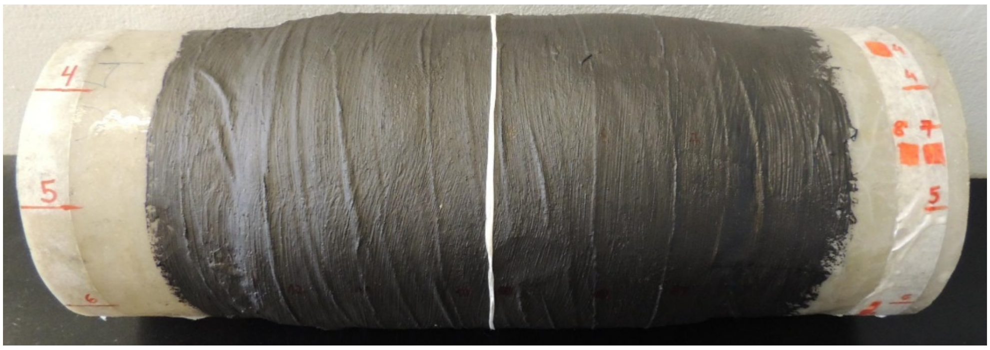


Figure 2 – Photography of the laminated joint (S2) evaluated in this study.

The third sample (S3) is made of carbon steel substrate with dimensions of 150 mm x 100 mm x 4.7 mm with anti-corrosive composite coating (epoxy resin based). Before applying the coating, some notches were machined with different thicknesses and fulfilled with iron oxide on the substrate in order to simulate localized corrosion with the presence of undercoating solid corrosion products. The coating was applied over the acetate tape positioned on the substrate and then, this tape was removed and the coating film was applied on coating layer. In this way, a star-shaped region was created on the surface of the substrate, where there is no presence of the coating layer, simulating adhesion failure in this region. Figure 3 shows the photography of this sample.

Figure 3 – Photography of the front side of the sample S3.

For the inspection of these samples, the Flir SC5600 thermographic camera was used simultaneously with the IR-Box system for the thermal excitation of the samples, both positioned in the reflection mode. This thermal stimulation system is controlled through IR-NDT software, which is responsible for the control of the lamps, the storage of thermographic images and the choice of data processing algorithms according to the modality of thermography to be applied.

The computational simulation model to be used in this paper was created in COMSOL Multiphysics software, versions 4.4 and 5.1. In this model was used the heat transfer module in solids, whose physical phenomena are applied in 3 dimensions (3D) and the evolution of temperature was time dependent, according to the principle of Pulsed Thermography technique. In addition to the equations describing the heat transfer in the three forms (conduction, convection and radiation), a heat flux was also added in the model in order to simulate the heating generated by the lamps on the surface of the sample.

3. RESULTS AND DISCUSSION

In order to evaluate the ability of the thermography technique to detect defects in composite adhesive joints, inspections by the Pulsed Thermography (PT) in sample S1 were performed both inside the joint and also from the outside the joint. The result of the inspection is presented in the form of a sequence of thermograms and the thermogram that produced the highest thermal contrast for each side of the sample is presented in Figure 4 (b). In addition, it was also evaluated the Pulsed Phase Thermography (PPT) on the inspection inside of the joint, as shown in Figure 4 (b). Analyzing these results, it is possible to observe that the PT was able to detect the defects of lack of adhesive when the inspection was carried out inside the joint even with a low thermal contrast, but the application of the PPT was able to highlight the two defective regions due to the greater contrast of the phase obtained.

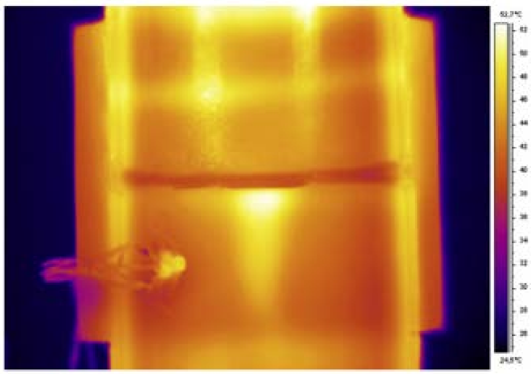


Figure 4 – Thermographic image at the time of highest contrast obtained by Pulsed Thermography performed on the inner side of the adhesive joint (sample 1).

The sample S2 was inspected by the three thermography modalities (PT, PPT and LT), in this region of the sample being inserted a delamination defect between the composite layers in the joint. The results obtained by each modality of thermography are presented in Figure 5 and these show that even in the simplest modality of thermography (PT), the defect could already be detected, however, the PPT and LT modalities presented a higher contrast in the region of the defect, allowing a better visualization of the contour and positioning of the same.

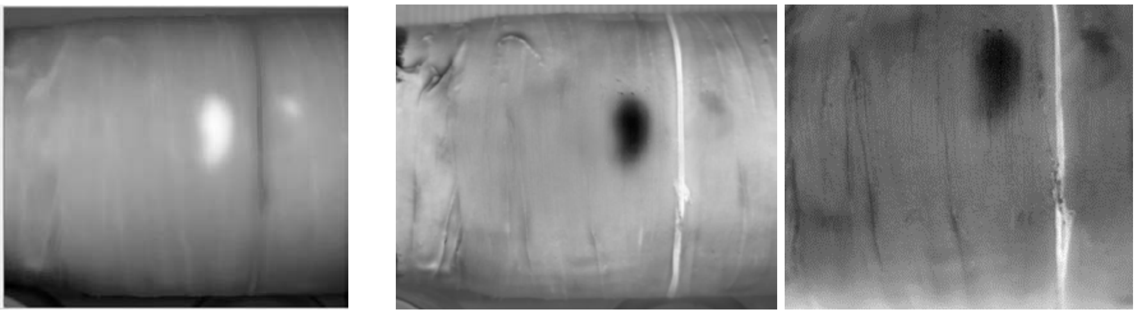


Figure 5 – (a) Thermographic image obtained by Pulsed Thermography, (b) phase image obtained by Pulsed Phase Thermography and (c) phase image obtained for Lockin Thermography with frequency of 0.01 Hz.

The higher contrast thermogram obtained for the sample S3 shows that the Pulsed Thermography was able to detect the two notches defects simulating the loss of thickness in the substrate and also the defect (star shape) simulating the adhesion failure. In addition to the defect type, this result shows that both the geometry of the defects and their thickness did not influence the detection when the inspection is performed on the front side of the sample. The presence of iron oxide filling the defects also did not generate any influence on the detection of defects by the thermography technique.

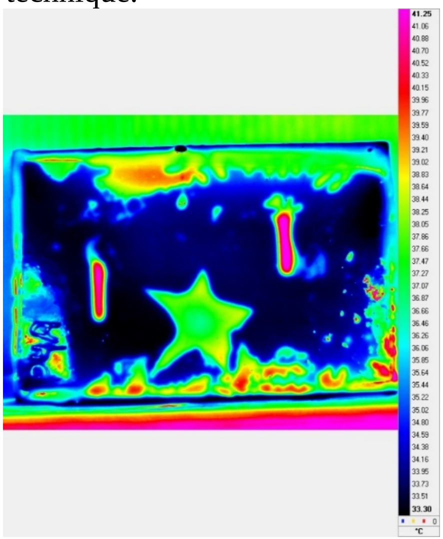
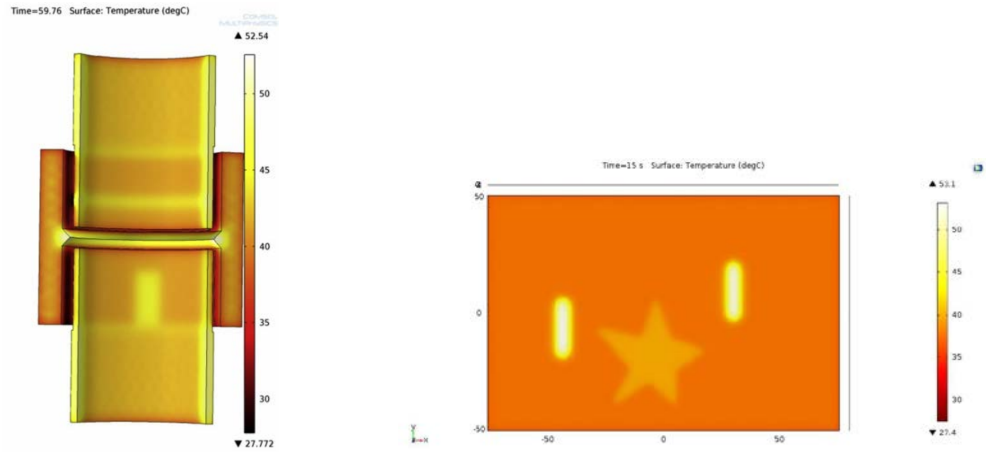


Figure 6 – Thermographic image at the time of the highest contrast obtained by Pulsed Thermography for the sample 3.

In Figure 7, the higher thermal contrast images obtained by the computational simulation of samples S1 and S3 are presented. According to the images, it is possible to observe that there is a behavior regarding the detection of defects very similar between the results obtained experimentally (Figure 4(a) and Figure 6) with the simulated ones. In addition, the thermal behavior, analyzed through the evolution of temperature in the two samples for each of the methodologies (experimental x simulation) also presented a great coherence.



(a) (b)

Figure 7 – Image obtained by the computational simulation of the pulsed thermography showing the temperature distribution on the surface of the: (a) sample S1 and (b) sample S3.

4. CONCLUSIONS

According to the results obtained, the use of the Active Thermography technique for the inspection of adhesive and laminated composite joints showed the potential of the technique for the inspection of composite materials of high thicknesses (above 5 mm). This study becomes promising because most of the works published in the literature are restricted to the evaluation of the technique in low thickness composites (below 5 mm), which demonstrates the challenge of this study. Another application of the technique studied in this paper was the inspection of composite coatings that are commonly used in storage tanks. Although visual inspection is the most used for inspection of these materials, the active thermography inspection has proved to be a powerful tool to detect defects that are common to occur (adhesion failure and localized corrosion on the substrate) and are not detectable by visual inspection.

By comparing the results for the two methodologies evaluated in this study (experimental and simulation), they showed a great similarity both in relation to the thermal behavior and in relation to the detection of the defects, thus allowing the validation of the model developed in this study. With this, the model created proved to be reliable and useful in to the reproduction of physical phenomena involved in the experiments. These results become interesting since the creation of a model by computational simulation able to reproduce the experimental test becomes a powerful tool for both in industry and in research since it allows the study of the best parameters to be used in the inspection, thus optimizing the results, both from the point of view of time and resources.

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