Stimulated thermography as non-destructive testing to assess the structural integrity of aeronautical component in CFRP

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Abstract

Composite materials are widely used in various applications, particularly in lightweight aeronautical and aerospace structures. These materials, during both manufacturing and service conditions, must be inspected to evaluate and characterize the presence of defects such as delamination, impacts, resin pockets, and porosity.

Nowadays, various non-destructive techniques (NDTs) are employed for the maintenance of mechanical components. However, these techniques typically require a significant amount of time, direct contact with the component, and the involvement of a qualified operator. In this context, thermal methods offer several advantages over traditional NDT techniques. These advantages include an easy and flexible test set-up, as well as the capability to perform in situ tests on components subjected to operational loads.

In this study, an experimental investigation was conducted to assess the effectiveness of different stimulated thermographic techniques in detecting delamination in aeronautical components made from Carbon Fiber Reinforced Polymers (CFRP). The findings of this research highlight the potential of thermographic methods to provide reliable, efficient, and non-invasive inspection solutions for composite materials in critical aerospace applications.

Keywords: composite materials, non-destructive testing, infrared thermography, ultrasounds, Carbon Fiber Reinforced Polymers (CFRP).

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP), and composite materials in general, are extensively used in the aeronautical field and related applications due to their lightweight properties. These materials offer significant weight savings which are crucial for the performance and efficiency of aircraft. However, the harsh environmental and severe operating conditions to which these components are subjected necessitate rigorous inspection and maintenance protocols. These protocols often involve the extensive use of non-destructive testing (NDT) techniques to detect and characterize defects, allowing for the prevention of damage and the replacement of entire parts before failure occurs [1]-[2].

The primary technique currently established in this field is ultrasound testing (UT) [1]-[8]. This technique is governed by well-defined standards and involves procedures and instrumentation that are highly regulated. UT is well-known for its capability to accurately and quantitatively define the size and position of defects. However, this method has some limitations, including the requirement for direct contact with the inspected components and typically long inspection times.

Alternatively, stimulated thermography, particularly pulsed thermography (PT) and lock-in thermography (LI) [8]-[14], can be employed to offer several advantages. These techniques allow for the use of non-contact sensors that can provide full-field information about damaged areas. Modern infrared (IR) sensors are compact and portable, making them well-suited for in-service conditions and structural health monitoring approaches. Both PT and LT require an external heat source to thermally excite the component under examination. An infrared sensor then captures a series of images during the heating and cooling phases, which are subsequently analysed and processed to detect the defects and obtain quantitative information about the presence of defects and anomalies.

The literature contains numerous studies that demonstrate and discuss the potential of stimulated thermography for evaluating defects in composite materials [10]-[14]. While thermography is widely utilized for simulated defects and master specimens, its application becomes more complex when dealing with real defects and components [15]. Detecting and localizing real defects is often more challenging than dealing with simulated defects, such as teflon inserts or flat-bottom holes, because real defects typically have lower reflection coefficients, which adversely affect signal contrast and defect detection. Moreover, real geometries and components require the development of precise procedures and post-processing algorithms tailored to specific applications.

In this work, starting from some results previously presented in [15] by D'Accardi et al., experimental tests were carried out on a real aeronautical component made of CFRP with existing delaminations, investigating the entire component (not only one sector) and applied different techniques, post-processing algorithms [17]-[24] and procedures for data analysis. This investigation employed a different low-cost set-up, adaptable to in-service conditions, using a microbolometer IR camera and halogen lamps as the thermal excitation source. The aim is to assess the feasibility and effectiveness of this set-up in detecting and characterizing delaminations within real-world aeronautical components, with the idea to understand the capability of this technique as structural health monitoring (SHM) methodology.

Moreover, this study aims to characterize real defects using thermography and explore the potential integration of this technique with conventional inspection methods such as UT. Through this investigation, the aim is to enhance the reliability and applicability of thermographic methods in NDT of composite materials.

2. Materials and Methods

2.1 Specimen and experimental set-up

In this study, a detailed analysis of a stringer assy as a real component from the Bombardier product line Alenia Aermacchi was carried out, made of composite material (CFRP). The component can be divided into two main sections: the cap and the web. The analysis focused specifically on the cap, an area where widespread delaminations across its entire surface. The cap has a length of 98 mm and a thickness of 2.76 mm (15 plies), while the web shows a thickness of 5.2 mm (30 plies). Below, an illustrative photo of the analysed component is reported (Figure 1).

Figure 1 - Stringer assy as investigated real component.

Different tests were carried out, developing two distinct experimental configurations: one tailored for LT analysis and another for PT. Each set-up was meticulously designed to suit the specific requirements of the testing methodologies employed. In both configurations, a reflective set-up was adopted, ensuring that the excitation sources and the thermal imaging camera were positioned on the same side as the specimen under examination.

The PT tests were carried out using two flash lamps for a total energy of 6 kJ. A cooled IR sensor was adopted to acquire the data which is a FLIR X6540 thermal camera, specially designed for high-speed imaging and thermal analysis. This set-up allowed a rapid thermal excitation and the capture of dynamic thermal responses, enabling the detection and characterization of defects within the composite material (Figure 2). To achieve high-resolution results with the pulsed thermographic technique used for the analysis, the entire length of the cap had to be divided into 14 sections, each measuring 70 mm in length.

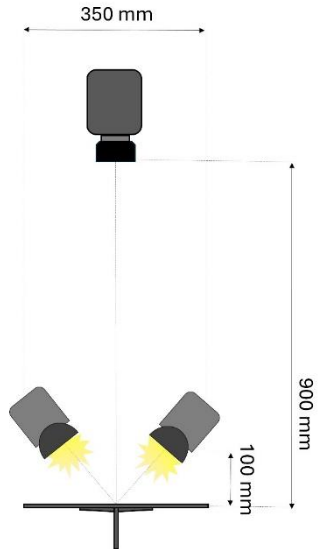


Figure 2 – PT set-up.

In Table 1, the adopted parameters are both for acquisition and excitation.

Excitation - Flash Lamps		Acquisition - IR cooled sensor FLIR X6540sc		
Energy [kJ]	Excitation time [ms]	Test duration [s]	Frame rate [Hz]	Resolution [mm/pixel]
6	3	8	100	0.17

Table 1 – Acquisition and excitation adopted parameters for PT tests

The LT set-up was specifically developed to explore the possibility of detecting delaminations using low-cost and scalable equipment suitable for industrial applications. This approach was considered due to the high costs associated with flash lamps, which are commonly used in PT and not suited for an SHM approach. By utilizing more affordable halogen lamps, the LT set-up aims to provide a cost-effective alternative without compromising the ability to accurately identify internal defects. A square wave has been used to reduce the time related to acquisition and data processing with the possibility of having in one test the amplitude and phase maps related to the main excitation period and the harmonics of higher order, related to more superficial indications.

Moreover, for the LT set-up, the experimental set-up involves the use of a FLIR 655sc microbolometric thermal camera to further reduce the costs related to the experimental set-up (Figure 3). In this case, to reduce the time for testing and data analysis, the component was divided into 7 different sectors, with a reduction of geometrical resolution. Table 2 reports the parameters related to the experimental set-up.

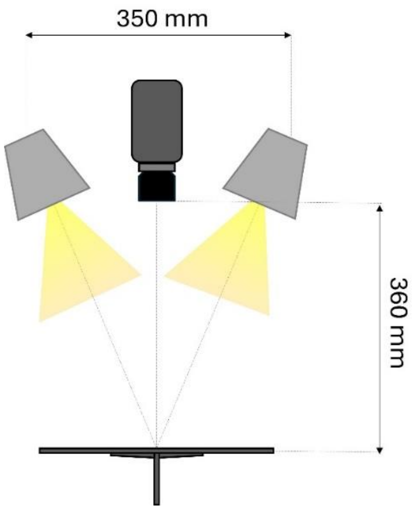


Figure 3 – LT set-up.

Excitation - Halogen Lamps			Acquisition - IR microbolometer sensor FLIR A655sc	
Power [kW]	Period [s]	Number of Cycles	Frame rate [Hz]	Resolution [mm/pixel]
1	5	3	20	0.23
	15		7	
	30		4	

Table 2 - Acquisition and excitation parameters for LT tests.

To validate the use of both thermographic techniques, ultrasonic tests were carried out using the same set-up reported in [15]. The integration of this ultrasonic technique ensured a comprehensive evaluation of the materials, allowing for cross-validation of the results obtained through thermographic methods.

2.2 Data analysis procedure

For the analysis of the acquired thermographic data, two different post-processing algorithms were adopted to obtain quantitative information, tailored to the specific thermographic techniques used; in particular, Principal Component Analysis (PCA) [25]-[28] was adopted to analyze PT tests, instead the signal reconstruction algorithm [14], [18] was used in case of LT. The procedures for data analysis are different for the two techniques; in the case of PT tests, different truncation window sizes [26] are available for further analysis. Instead, after a LT test single maps related to phase and amplitude results are available. Here both procedures are explained in detail.

Pulsed thermography tests

For the Pulsed thermography tests, Principal Component Analysis (PCA) was adopted. PCA is a powerful statistical procedure that transforms the data into a set of linearly uncorrelated variables known as principal components. By reducing the dimensionality of the data, PCA emphasizes the most significant features, making it easier to detect and visualize defects within the material. This method is particularly effective in highlighting variations in thermal responses that correspond to underlying structural anomalies.

This algorithm was applied with different truncation window sizes to evaluate the influence of this parameter. Specifically, four temporal windows were analyzed: 1 second, 2 seconds, 4 seconds, and 7 seconds. Theoretically, as the inspection window changes, the contrast between a defect and a related sound area is different.

The evaluation of the most suitable truncation window size and the corresponding component was based on the analysis of the highest normalized thermal contrast [18]. The analysis procedure is resumed as follows:

1. Initially, the PCA algorithm was applied to each of the four thermographic sequences corresponding to the four different truncation window sizes (1 second, 2 seconds, 4 seconds, and 7 seconds);

2. An analysis of the normalized contrast (CNR) was then performed, selecting a sound area of approximately 150 pixels for each sector based on the obtained UT results (similar to the procedure adopted in [15]);

3. For each sequence, a map of the maximum normalized contrasts was extracted (absolute value);

4. By comparing these four maps, the truncation window size that exhibited the highest normalized contrast in the area interested by a given defect (detected by UT) was selected;

5. After determining the optimal truncation window size, a further analysis was carried out to select only one among the N-th principal components, considering the same criterion (based on CNR) and so by considering the map related to the PCA result and the related N-th component map.

This procedure allowed for the selection of the specific result where the defects were most clearly visible. A scheme that summarizes this procedure is then reported in Figure 4. In case of a different indication in terms of truncation window size that maximizes the contrast or, on the other hand, a different principal component when more than one defect is detected, it means that the defect depth can be different, or that more, in general, the geometrical characteristics related to the defect can influence the normalized contrast itself. The quantitative characterization of a real defect involves a comprehensive analysis that is related to the merging of different thermographic parameters; in this case, the application of the PCA algorithm and the study of different truncation window sizes can lead to a different result for many reasons that can be not directly correlated to defect depth.

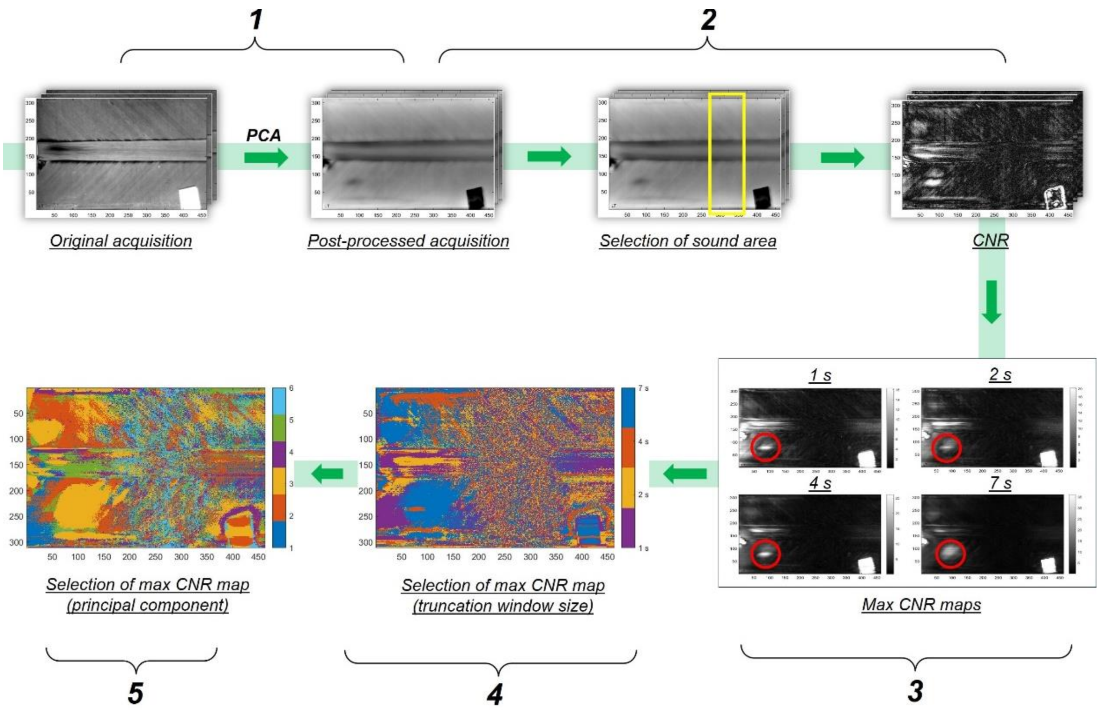


Figure 4 – Scheme of the summarized procedure.

Lock-in thermography tests

As shown in the previous section, a series of experimental tests were conducted changing the excitation period to identify the optimum one for the investigated real delamination. As well-known, each excitation period is related to a precise depth of inspection. It was found that acquisitions with a period of 15 seconds provided the most reliable results.

The signal reconstruction algorithm was adopted to generate both phase and amplitude images [14], [18]. The best results are then reported in the next section to demonstrate the feasibility of this low-cost approach.

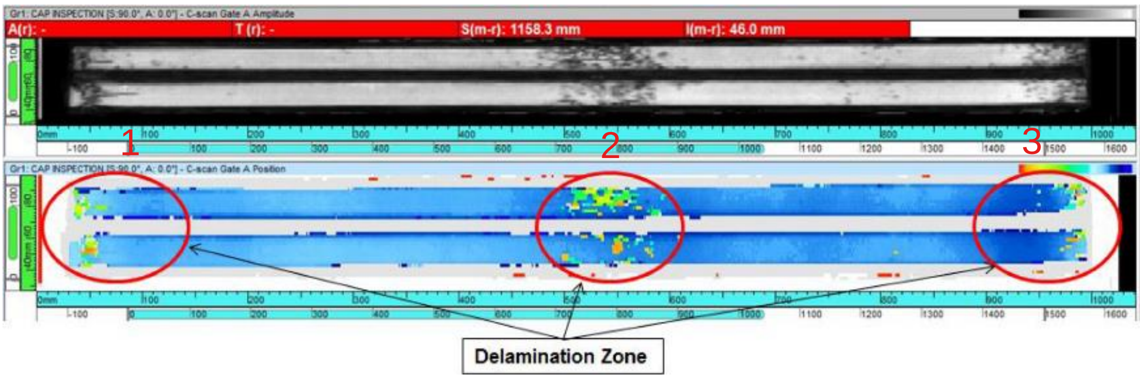
3. Results

Within this section the obtained results were reported; in particular, the maps obtained after the application of both PT and LT techniques were reported, considering the procedure for data analysis previously explained for both the configuration and specifically the results related to the sectors that show the presence of defects after UT tests. In the case of PT analyses, as an example of the obtained results, only one truncation window size and one component that optimizes the results in case of a specific defect for each sector have been selected.

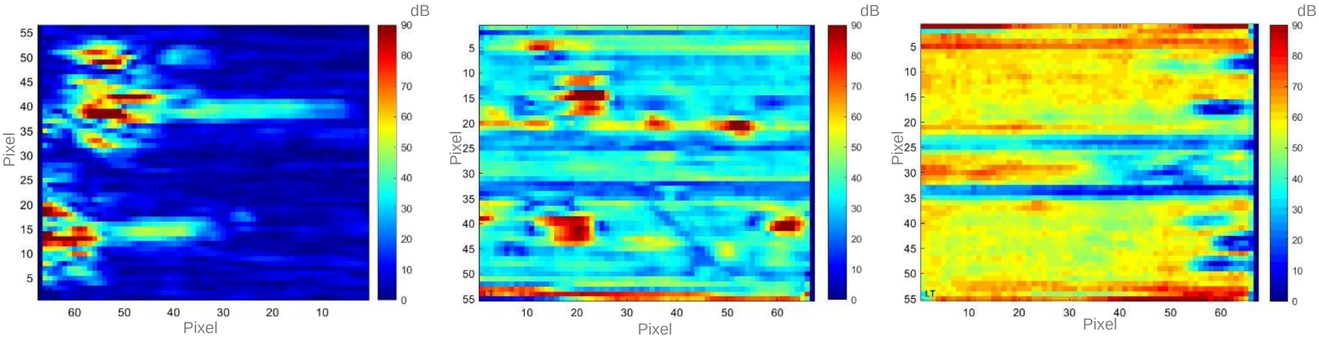
3.1 Ultrasonic tests

The following sections present the results of the ultrasonic testing performed on the component using a commercial Semi-Automatic PE PHASED ARRAY (PAT System) to inspect the cap and web. These results serve as the baseline for the subsequent comparison and evaluation of thermographic techniques aimed at detecting delaminations in CFRP.

As illustrated in the Figure 5a below, the defects are localized in three specific areas of the analyzed specimen. The same Figure 5 (b, c and d) includes also detailed images of the three defective zones. These results are related to the amplitude signal and represent a C-Scan of the component at a specific depth. As described in [15], different measurements were realized with a step of 0.3 mm (axial resolution) to display the defects at each depth. The results reported in Figure 5 for the different sectors are related to a depth range that optimizes the signal to noise ratio in correspondence with the area interested by defects; in particular for section 1 that depth range is 1.2 mm – 1.5 mm (Figure 5b), for section 2 is 0.6 mm – 0.9 mm (Figure 5c) and for section 3 is 0.3 mm – 0.6 mm (Figure 5d). The same scale is set to compare the obtained results. These detailed views highlight the precise locations of the delaminations in the same sectors analyzed with PT and LT tests.



(a)



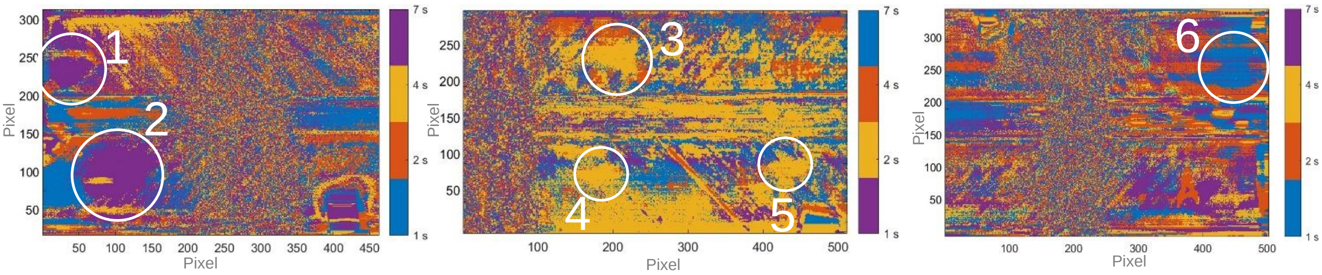
(b) (c) (d)

Figure 5 – (a) C-Scan of the whole component, (b) C-Scan of section 1, (c) C-Scan of section 2, (d) C-Scan of section 3.

3.2 Pulsed tests

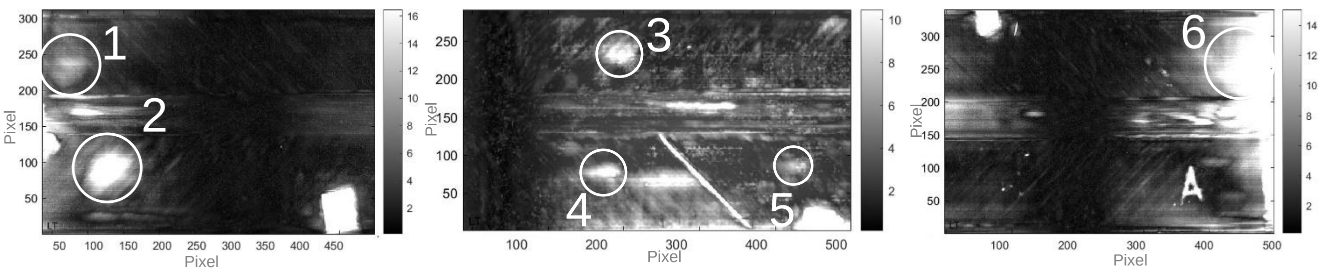
Figure 9 presents the results obtained for the three defective sections of the analyzed component (the same sections discussed in the previous paragraph) considering the PT technique. The PT tests, as detailed in the previous chapter, were analyzed using the PCA algorithm and the procedure for data analysis explained before. In particular, for section 1 the adopted procedure sees the selection of the window related to 7 seconds (Figure 6a) and the third component (Figure 8a), for section 2 has been selected 2 seconds as truncation window size with the highest normalized thermal contrast (Figure 6b) and the third component (Figure 8b), lastly, in section 3 the chosen procedure involves selecting the 1 second window (Figure 6c) and the fourth component (Figure 8c).

The obtained results are in agreement with UT maps and indications, revealing the possibility of using this technique and in particular PT for the detection of these defects, with a good contrast to noise ratio.



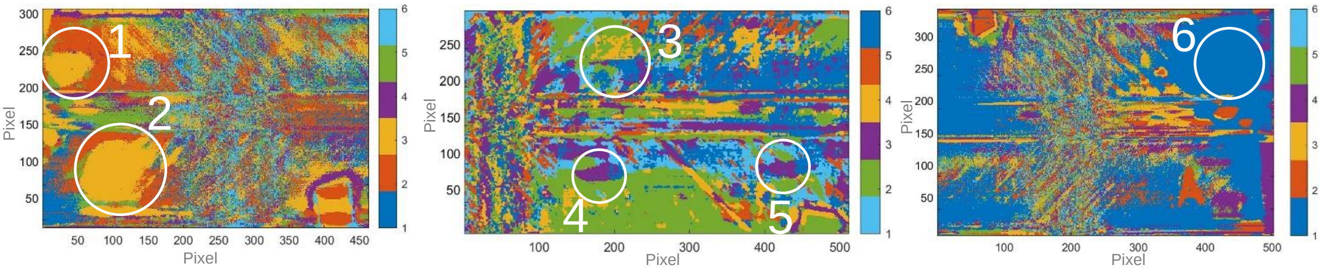
(a) (b) (c)

Figure 6 – Superimposition of the four maximum CNR maps related to the four truncation windows: (a) section 1, (b) section 2, (c) section 3.



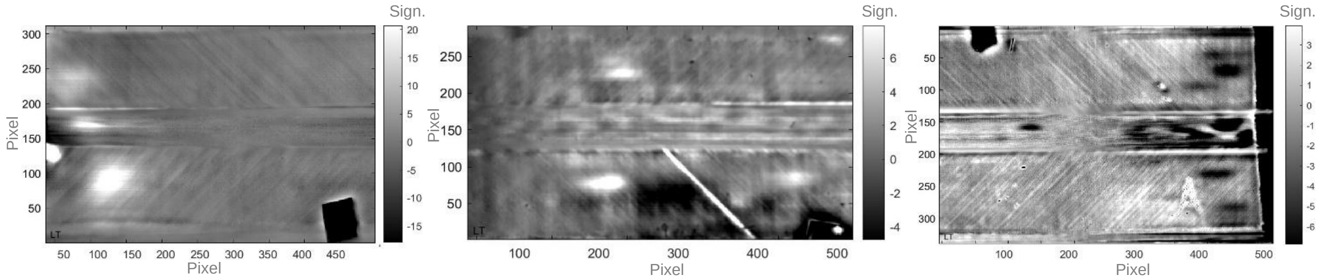
(a) (b) (c)

Figure 7 – Max CNR map related to selected truncation window size: (a) section 1, (b) section 2, (c) section 3.



(a) (b) (c)

Figure 8 – Superimposition of the six PCA principal components: (a) section 1, (b) section 2, (c) section 3.

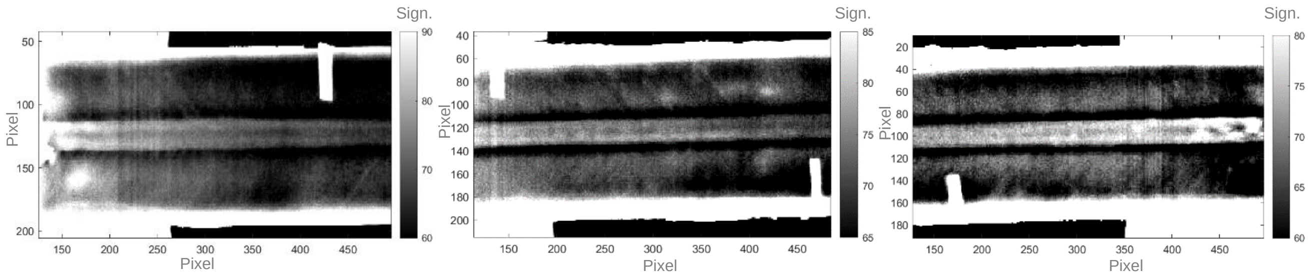


(a) (b) (c)

Figure 9 – PCA map related to the selected truncation window size and the corresponding N-th principal component: (a) section 1, (b) section 2, (c) section 3.

3.3 Lock-in tests

The following sections present finally the LT results (Figure 10). These sectors correspond to areas previously analyzed by ultrasonic and PT inspections, considering a low-cost set-up and a different geometrical resolution (2 sectors were shown together in the same image). The images are related to the obtained results in terms of amplitude, which shows after a qualitative analysis a higher contrast with respect to phase results within the defective areas.
Some indications in the area interested by defects, especially in the case of sector 1 and sector 4, were obtained, revealing the possibility of further scaling the use of this technique with the use of a low-cost set-up and saving also time for tests and analyses.



(a) (b) (c)

Figure 10 - Amplitude map of LT tests with a period of 15 seconds: (a) section 1, (b) section 2, (c) section 3.

4. Conclusions and further developments

To summarize, ultrasonic testing, a well-established and widely trusted non-destructive testing technique, served as a reference technique for evaluating the capability of the thermographic methods for the inspection of real components and characterization of real defects, as delaminations in CFRP material. This comparison involved a detailed assessment of the capability of the thermographic techniques to identify and characterize defects considering different techniques and approaches aimed to further reduce time testing, analysis and costs related to the adopted set-up.

The comparative analysis revealed insights into the relative strengths and limitations of each employed thermographic technique. It provided a comprehensive evaluation of their potential as reliable non-destructive testing methods for CFRP materials. A quantitative approach has been proposed to characterize real defects, promoting the use of this technique as quantitative non-destructive testing with results comparable with UT. The obtained results revealed the presence of delamination widespread in the entire component, specifically affecting the structural integrity of three sectors, obtaining good results in agreement with UT, both considering PT and LT as thermographic techniques.

Further studies will investigate the possibility of further analyzing the data that come from LT in order to increase the signal to noise ratio and obtain quantitative information. Other sensors in the class of microbolometer cameras will be adopted in other to further reduce the cost related to the instrumentation and maybe carry out simultaneous tests on the entire component in one slot considering more than one camera.

5. Funding

This work was supported by the DiTECO project (Defects, damage and repair TEchniques in the production processes of large structures in COmposite - PON3 Axis I Title III) funded by MIUR.

Part of the work has been Financed by the European Union - NextGenerationEU (National Sustainable Mobility Center CN00000023, Italian Ministry of University and Research Decree n. 1033–17/06/2022, Spoke 11 - Innovative Materials & Lightweighting). The opinions expressed are those of the authors only and should not be considered as representative of the European Union or the European Commission's official position. Neither the European Union nor the European Commission can be held responsible for them.

6. Acknowledgments

With great sadness and profound gratitude, the authors wish to remember Dr. Fania Palano, who passed away on December 7, 2023. Dr. Palano has carried out ultrasonic tests obtaining the raw data further analyzed in this work.

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8. Copyright Statement

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