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NDT characterisation of carbon-fibre and glass-fibre composites using non-invasive imaging techniques

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Abstract

The prerequisite for more competent and cost effective transport has led to the evolution of innovative testing and evaluation procedures. Non-destructive testing and evaluation (NDT & E) techniques for assessing the integrity of composite structures are essential to both reduce manufacturing costs and out of service time of transport means due to maintenance. Smart methods for assessing the integrity of a composite structure are essential to both reduce manufacturing costs and out of service time of the structure due to maintenance. Nowadays, thermal non-destructive testing (NDT) is commonly used for assessing composites. This research work evaluates the potential of various infrared thermography (IRT) approaches for assessing different types of fabricated defects (i.e. impact damage, inclusions for delaminations, etc) on Glass Fibre Reinforced Polymer (GFRP) and Carbon Fibre Reinforced Polymer (CFRP) plates. Measurements were performed using LWIR and three active approaches: a) pulsed thermography using the flash method (xenon flash lamps), b) transient themography using IR-heating pulse, and c) thermographic inspection for cooled sample by freezing in -20 °C and then use monitoring. Furthermore, integrated flash thermography by employing a MWIR system was also used. Finally, NIR imaging was also utilised for the inspection of the GFRP and CFRP plates.

1. Introduction

Infrared thermography is a nondestructive testing and evaluation (NDT&E) technique allowing fast inspection of large surfaces. Figure 1 illustrates the different approaches to infrared thermography [1]. As it is well-known, in the *passive* approach the features of interest are naturally at a higher or lower temperature than the background. This is the case, for instance, of surveillance of people on a scene and a number of medical and veterinarian applications.

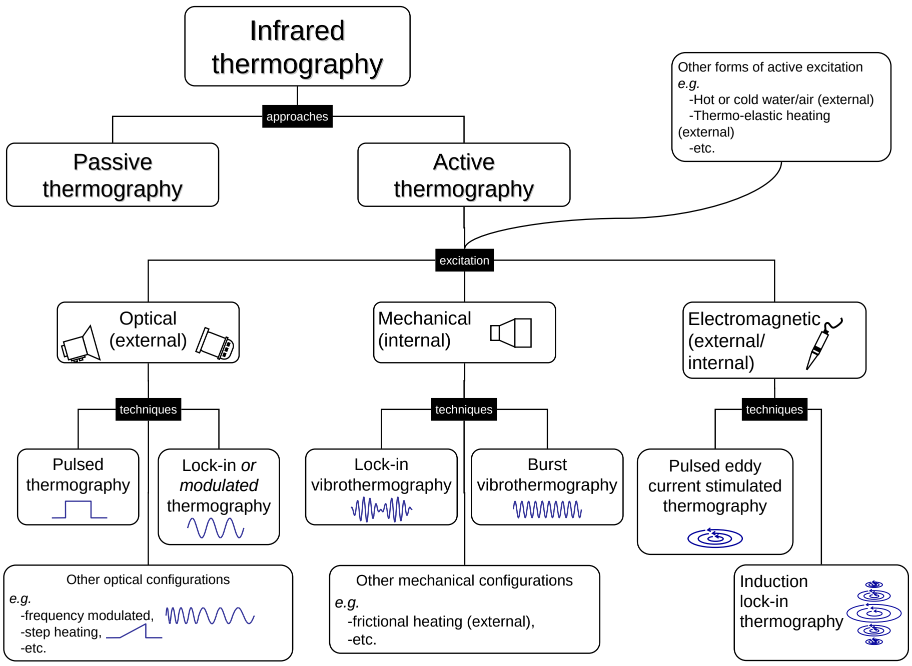

Figure 1. Infrared thermography approaches.

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The *active* approach, on the contrary, requires an external energy source to produce a thermal contrast between the feature of interest and the background. This is the most suitable configuration for composites NDT&E since such parts are normally at thermal equilibrium during the inspection and is the subject of this investigation. Practically *any* energy source can be used to stimulate the specimen being inspected, from cold or hot air to water jets, or frequency and amplitude modulated acoustic waves. Of course, the choice of one or the other source will affect the results. The final decision on the energy source should be made depending on the application.

In this study, different thermography tests were performed for glass fibre reinforced laminate and carbon fibre reinforced laminate test samples. The experimental results presented herein, allowed deriving some conclusions about the most suitable approach for each particular case.

2. Inspection of GRP & CRP plates

Photographs and a schematic of the plates containing different types of fabricated defects are presented in Figures 2 and 3 respectively.

a) b)

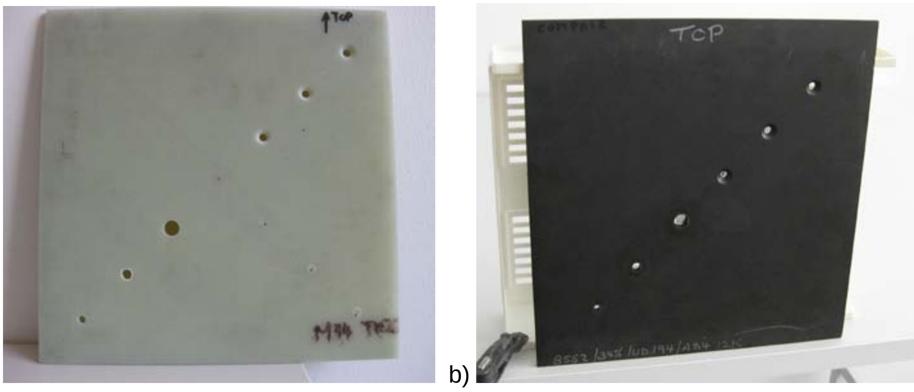

Figure 2. a) Glass fibre reinforced test laminate. b) Carbon fibre reinforced test laminate.

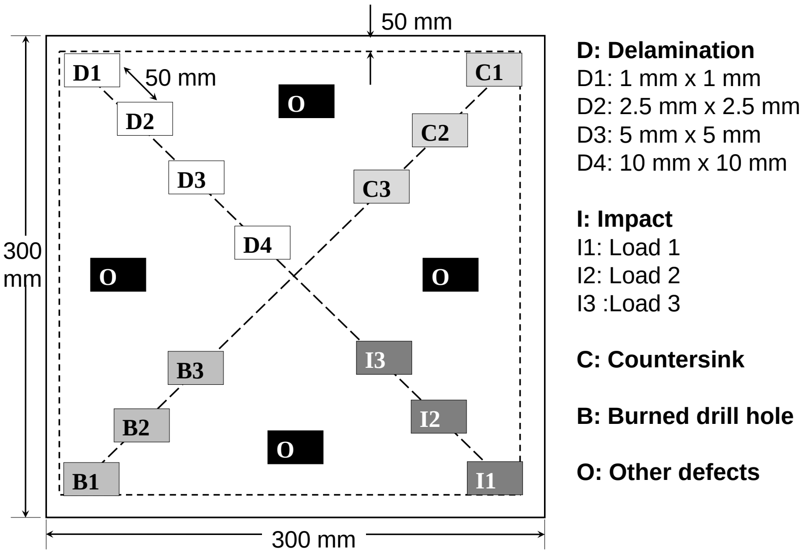

Figure 3. Composite samples investigated.

Firstly, two different LW-IR cameras that were taken into the test and they were ThermaCAM™ S65 and and FLIR P640.

Three active methods were used to induce the temperature difference to the samples:

- pulsed thermography (Figure 4): flash method (xenon flash lamps), 2 * 4 kJ, heating time 0.1 second, monitoring 10 to 20 seconds, 50 Hz.
- transient themography (Figure 5): IR-heating pulse, heating time 30 seconds, monitoring 10 to 30 minutes.
- thermographic inspection for cooled sample (Figure 6): freezing in -20 °C, freezing time min 3 hours, monitoring 30 to 60 minutes.

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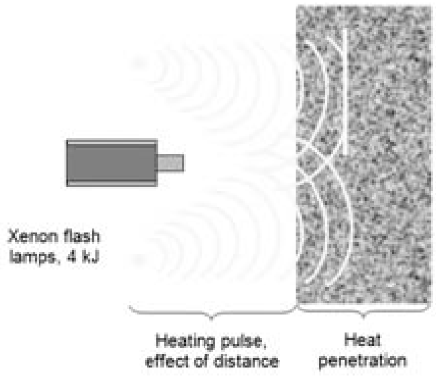

Figure 4. Principle of pulsed thermographic (flash method) measurements. Cooling behaviour of the sample monitored few seconds.

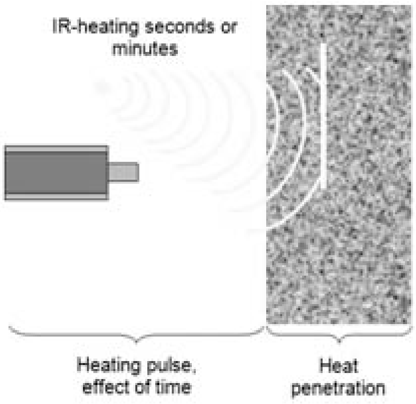

Figure 5. Principle of transient thermographic (IR-heating) measurements. Cooling behaviour of the sample monitored 10 to 30 minutes.

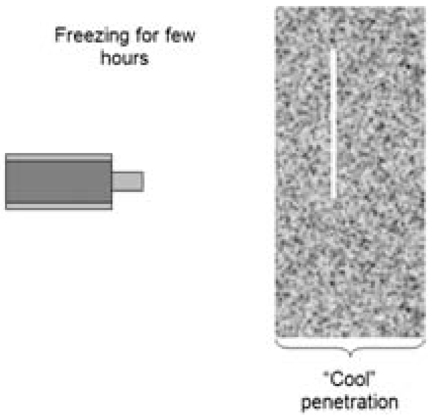

Figure 6. Principle of thermographic inspection for cooled sample. Warming behaviour of the sample monitored 30 to 60 minutes.

The biggest difference between the two thermographic cameras was the resolution, which in the P640 was doubled to both directions (x,y) compared to S65. Resolution of S65 is 0.65 mrad (320*240 pixels) and the resolution of P640 is 1.3 mrad (640*480 pixels). The thermal sensitivity of P640 is also a bit better 0.055 °C, compared to the thermal sensitivity of S65 (0.08 °C).

The main target was to compare different heating methods and the reliability to find hidden defects. Heating pulse with flash method was in 50 cm distance for both of the xenon lamps. Cameras were adjusted to show the whole sample. Due to the different optics, the distances of the cameras were different, and the second aim of the tests was also to verify effect of camera resolution. Other test arrangements were kept constant (Figure 7).

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Figure 7. Test arrangement for the pulsed thermographic (flash method) measurements.

P640 shows very sharp image after the pulse, but image from S65 is quite blurred (Figures 8 and 9). The blurred effect seems to be both lower resolution of the camera, and that the image is a bit out of focus. The dimensions of the enhanced resolution can be seen from the spot, which shows the smallest area where the temperature can be measured reliably with the equipment. Spot circle of P640 is hardly visible but temperature of the smallest hole (down left corner) can hardly be measured reliably with S65, from the selected distance.

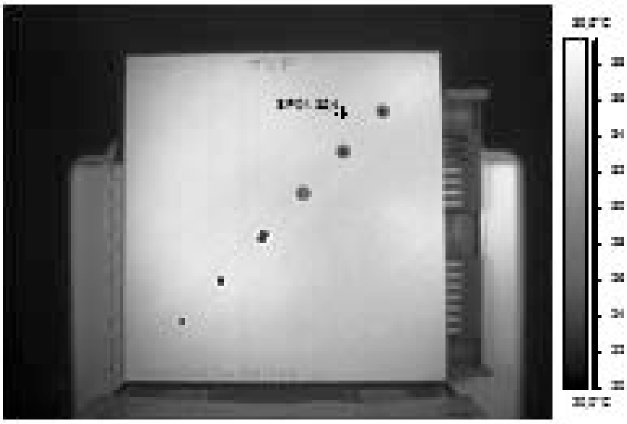

Figure 8. Flash method test with P640. Individual picture taken from the sequence.

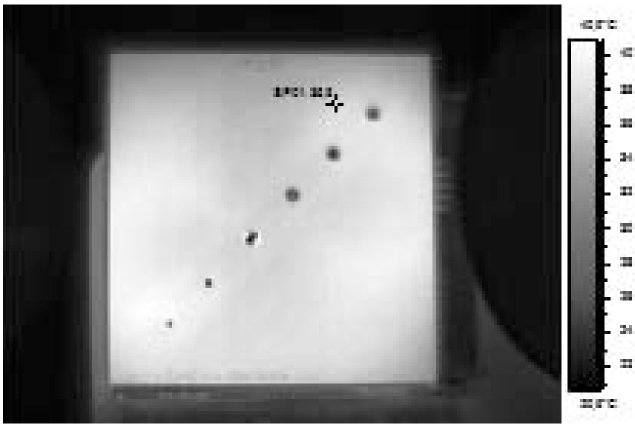

Figure 9. Flash method test with S65. Individual picture taken from the sequence.

Analysis show hidden defects in carbon fibre reinforced laminate on the right lower corner in front side (Figure 10). Rear side inspection reveals loose fibres in two drilling wholes (middle) (Figure 11).

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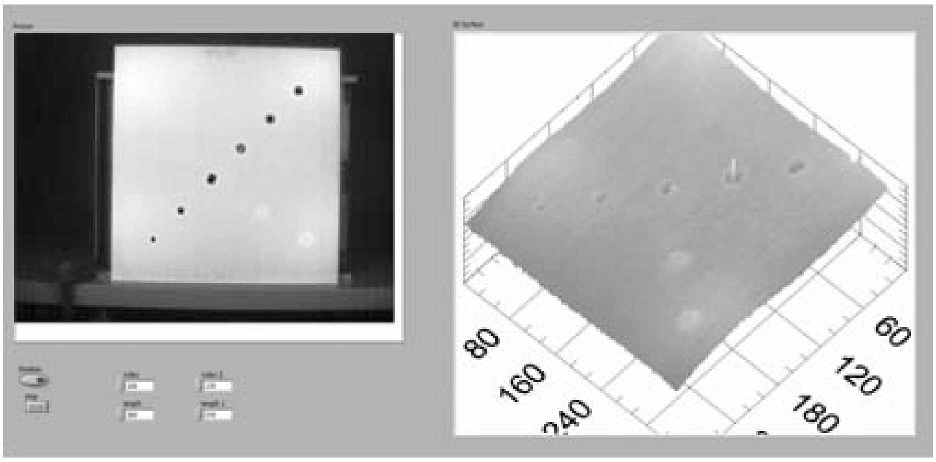


Figure 10. Flash method test with P640. Sample: Carbon fibre laminate, front.

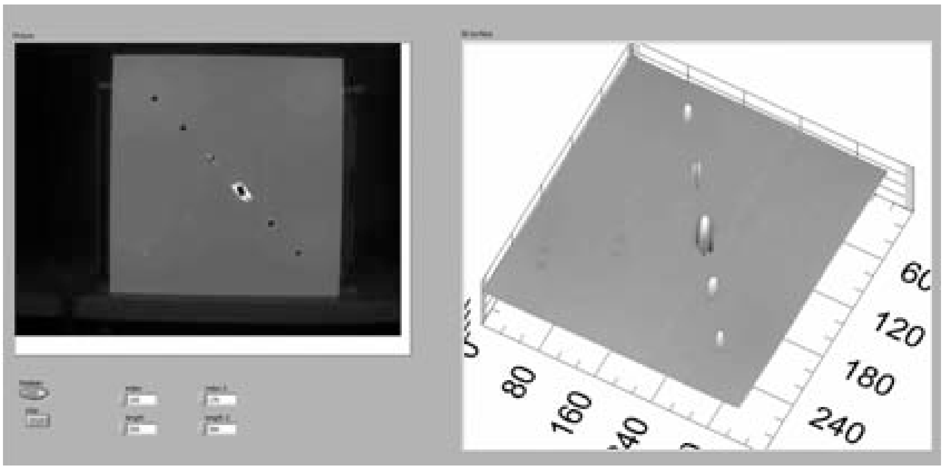


Figure 11. Flash method test with P640. Sample: Carbon fibre laminate, rear.

Glass fibre reinforced laminate shows some anomalies on front side diagonally close to the surface from upper left corner to the lower right corner (Figure 12). Rear side anomalies are in large area, but can be partly due to the dirt on the surface created during the manufacturing stage (Figure 13).

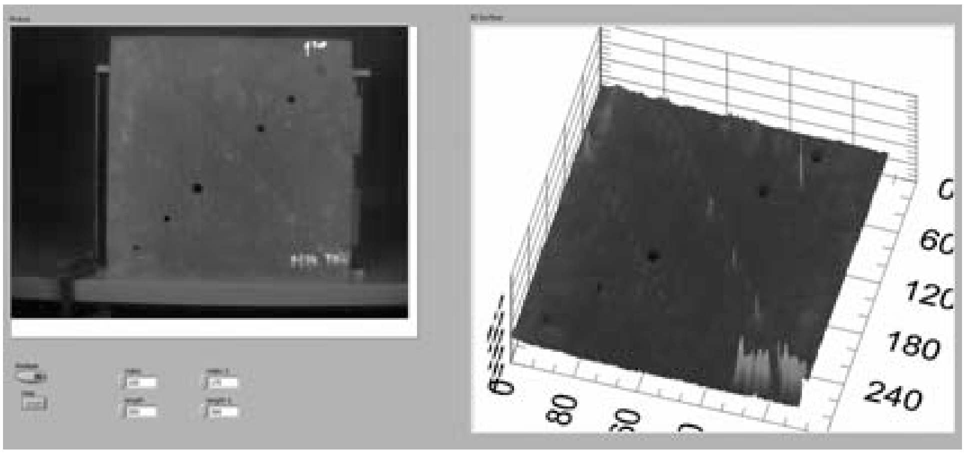


Figure 12. Flash method test with P640. Sample: Glass fibre laminate, front.

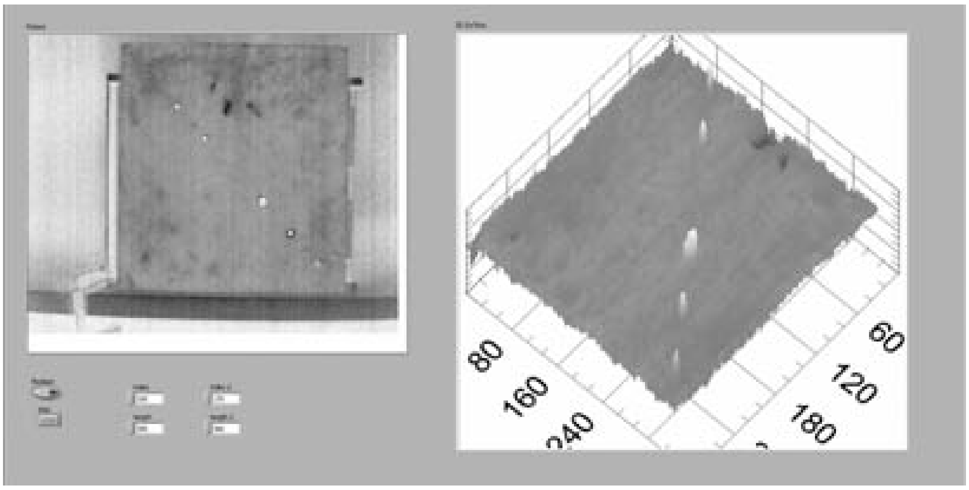


Figure 13. Flash method test with P640. Sample: Glass fibre laminate, rear.

Furthermore, there were more pulsed thermography tests that were performed with the aid of an integrated flash thermography system employing a MWIR camera.

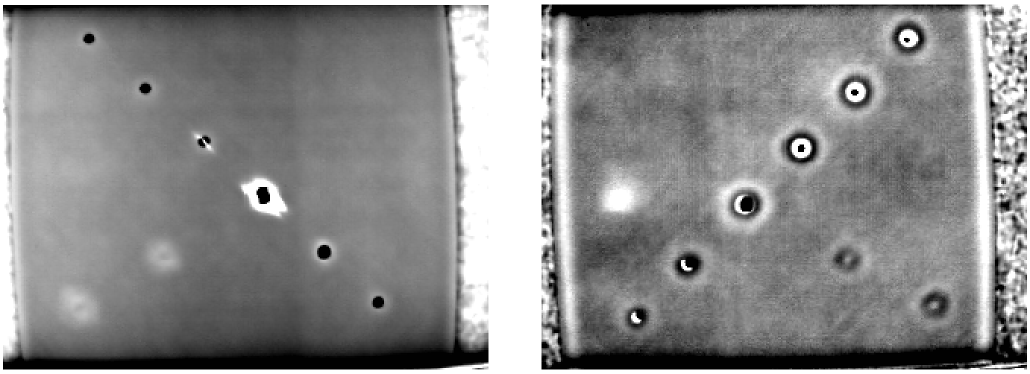


Figure 14. Transient thermography results on CRP sample presenting raw image acquired with a frame rate of 3.75 Hz from the back side (left) and 1st derivative image acquired with a frame rate of 15 Hz from the front side by using TSR approach (right).

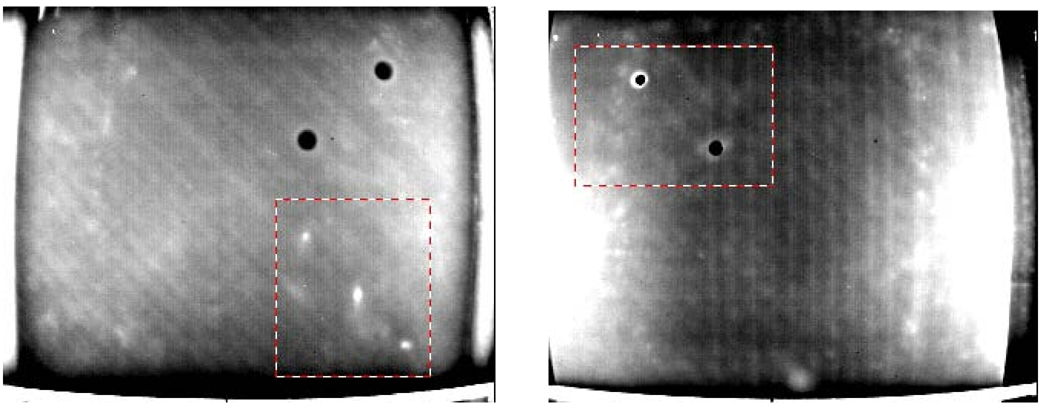
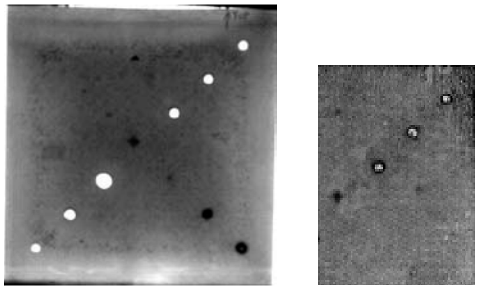


Figure 15. Transient thermography results on GRP sample presenting raw image acquired with a frame rate of 1 Hz from the front side (left) and another raw thermogram acquired with a frame rate of 2 Hz from the back side (right).

From the above results presented, it can be seen that different active thermography techniques can be used in the NDT assessment of composite materials. Selection of the most suitable energy source depends on the application. Optical pulsed thermography [2] is fast and easy to deploy. Although data are affected by different problems (non-uniform heating, emissivity variations, environmental reflections and surface geometry), there are numerous processing techniques available to counter these problems and therefore to obtain prompt results of reliable quality, as well as quantitative information in some instances [3]. Furthermore, every material responds differently to thermal excitation depending on the way it has been stimulated. Thermography based on optical techniques, in general, provide very good defect resolution [4]. However, results are strongly affected by surface features. Advanced signal/image processing is required to reduce their impact, i.e. PPT [5] and TSR [6] techniques allow detecting defects down to a depth of 2.5 mm, for defects having a size-to-depth ratio of approximately 2 and higher.

The samples were further investigated using a NIR camera (0.9-1.7 μm, 640x512 pixel resolution). NIR vision recovers the reflected or transmitted (non-thermal) radiation from or through the specimen in the near portion of the infrared spectrum (0.9-2.5 μm). This technique, commonly referred as reflectography (in reflection mode), is extensively employed in the examination of artworks where underdrawings (opaque to NIR radiation) can be detected through the painting layers (semi-transparent to NIR radiation) providing information about the integrity of the piece, intentional and unintentional alterations and artists' motifs. Nevertheless, to our knowledge, NIR vision has seldom been exploited for the assessment of industrial parts.

Figure 16 shows a NIR image obtained using an incandescent light in transmission as an illumination source. As can be seen from this figure, at least three of the delaminations ("D" defects) can be clearly identified on the GFRP sample. Evidences of the relative loading differences impact defects (type "I") can also be noticed. The countersink defects (type "C") and the burned drill holes ("B" type defects) of different sizes can be perfectly seen (holes), although no apparent differences between them can be made. Further testing with increased spatial resolution would be required for this manner. Nonetheless, this approach is not appropriate for CFRP samples. As a comparison, a result from IR thermography is presented in Figure 16b. The specimen's front surface was black-painted in this case. Some of the defects can be seen. For instance, one of the type "O" defects (at the left) cannot be detected by IR thermography but it is detected by NIR vision. These results demonstrate that NIR vision could be an interesting approach for the assessment of glass fibre components, whereas for CFRP is the other way around.



(a) (b)

Figure 16. Results by: (a) NIR vision, (b) IR thermography (processed using pulsed phase thermography).

3. Conclusions

Every material responds differently to thermal excitation depending on the way it has been stimulated. Thermography based on optical techniques, in general, provide very good defect resolution. However, results are strongly affected by surface features. Advanced signal/image processing is required to reduce their impact. For instance, PPT and TSR techniques allow detecting defects down to a depth of 2.5 mm, for defects having a size-to-depth ratio of approximately 2 and higher. NDT assessment can be applied to different materials, according to the case - application. The above paper presented results and their discussion using different techniques and/or approaches for evaluating composites.

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