PASSIVE INFRARED THERMOGRAPHY FOR DAMAGE MONITORING DURING STRUCTURAL TESTING OF CFRP PARTS

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Abstract

Infrared Thermography (IRT) is a Non-Destructive Evaluation (NDE) technique widely used for the inspection of composite structures. IRT can be (i) active, when the component is thermally excited by an external source of heat, or (ii) passive, when differences in either thermal-emissivity or temperature gradients related to subsurface structures are observed.
This work aims to use passive IRT for the detection of damage evolution in CFRP parts while performing mechanical tests, combined with image processing strategies. The heat release related to fiber/matrix failure or due to stress concentrators is recorded during tensile testing.

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP) are widely used in the aeronautic industry, because of its low weight and mechanical behavior, especially under fatigue loading. One of the main differences of the composite materials compared to metals is its lack of homogeneity, integrating carbon fibers in a polymeric resin matrix as one unique material. This means that under mechanical loading, discontinuities may appear as a result of fiber breakage, fiber/resin delamination, between others [1-2]. All these discontinuities carry the generation of local heat sources that can be visualized through an infrared camera [3].

Nowadays, other methods for mechanical testing monitoring are available, such as Digital Image Correlation (DIC) or Acoustic Emission (AE). The first one allows full field strain/displacement characterization, but the method is most of the time unable of detecting single fiber breakages [4]. On the other hand, AE testing offers a high detectability ratio of fiber breakage, however lacks in positioning [5].

Several investigations have been performed in the last years in order to monitor the damage evolution in composites materials during mechanical testing, providing good results [6]. The aim of this work is to improve the detectability of defect apparition during thermographic monitoring applying post-processing strategies, leading into an (i) easier interpretation and (ii) automatic evaluation of the thermographs. This final step could lead into an automated detection process.

2. Experimental

2.1. Materials

A rectangular woven CFRP (0/90) sample of 182.25x17.60 mm^2 and 4 mm thickness was mechanically tested.

2.2. Mechanical testing

Tensile test was performed using a universal testing machine Zwick Z100. The test consisted on one cycle, including a constant tensile loading displacement-rate (crossbar speed of 2 mm/min), followed by a constant stress plateau at 440 MPa and a return to zero.

2.3. Thermographic imaging

Passive infrared thermography was performed during mechanical loading using a FLIR SC7000 camera (which thermal resolution lower than 18 mK). A recording frame rate of 150 Hz was selected with image resolution of 320x376 pixels. The distance from the camera to the test specimen was 400 mm. Altair software (developed by FLIR) was employed for image recording and data post-processing as well.

3. Image Processing

After the thermal sequence is acquired, a post-processing strategy is performed in order to improve the quality of the results, both qualitatively (naked eye) and quantitatively (software assisted), and detailed below.

1. – The sequence is normalized, dividing all recorded frames by the first one in each sequence. This operation is performed through Altair software (FLIR), which allows the user to perform arithmetic operations with the thermographic images.

$$\overline{FR_i} = \frac{FR_i}{FR_0} \tag{1}$$

2. – After normalization of the image sequence, the detection of hot regions in the investigated sample, and related with fiber breakage, fiber-resin delamination, etc., can be performed. A method for automatic detection of frames containing indications has been developed. The last one is based on the arithmetic manipulation of the acquired sequences, and explained in the next section.

3. – Once all hot regions sources have been located in the normalized image sequence, it is necessary to obtain the temperature difference generated by the local heat dissipation at specific location. Taking into consideration, temperature normalization, this could be calculated as:

$$\overline{\Delta T} = \bar{T}(\overline{FR_i}) - \bar{T}(\overline{FR_{i-1}}) \tag{2}$$

4. Results & Discussion

View of recorded thermograph at with heat dissipation during fiber breakage is depicted in Figure 1. The last one includes processed images calculated as described in section 3. It is clearly noticed that the detection of damage apparition becomes much easier on the normalized and subtracted sequences, while it is difficult to observe in the original thermograph.

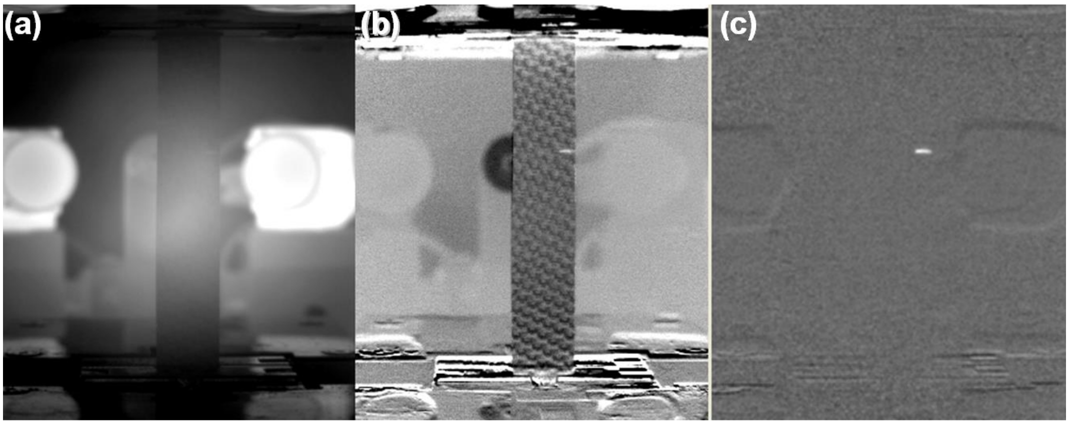

Figure 1. Thermogram (a) original, (b) normalized and (c) subtracted.

For automated detection of indications, two different approaches have been implemented:

(i) The first method is based in the “timing graph” of the maximum normalized temperature of the whole specimen, where the normalized temperature is extracted from the region of interest (ROI), only on sample area, by software analysis. The method is not sensitive enough for detecting low energy dissipation regions (related with the appearance of minor defects), since a low contrast is observed against the background signal of the ROI. It can be seen then (as example) in Figure 1b, that the upper part of the sample presents larger normalized temperature with respect of central and bottom regions. Therefore, the heat sources produced by low energy defects may not exceed most of the time this normalized maximum temperature.

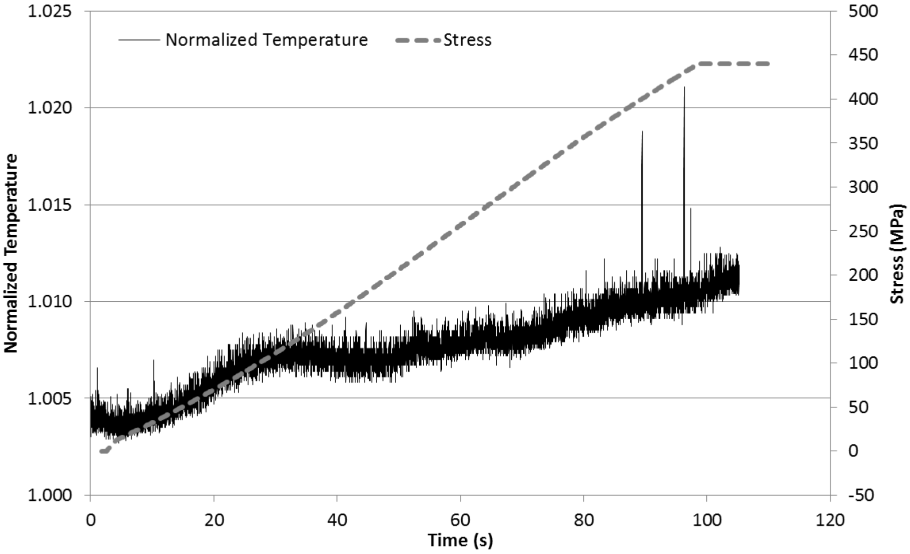

Figure 2. “Timing graph” of the maximum normalized temperature of the ROI during loading.

(ii) The second method consists on the subtraction of the previous frame for the whole normalized sequence. After this step, the background normalized temperature (of the ROI) is homogenized in each pixel image, and therefore any minor variation of local temperature can be detected. This can be seen in Figure 3, where more peaks and large contrast (of the previous recorded by the first method) are observable.

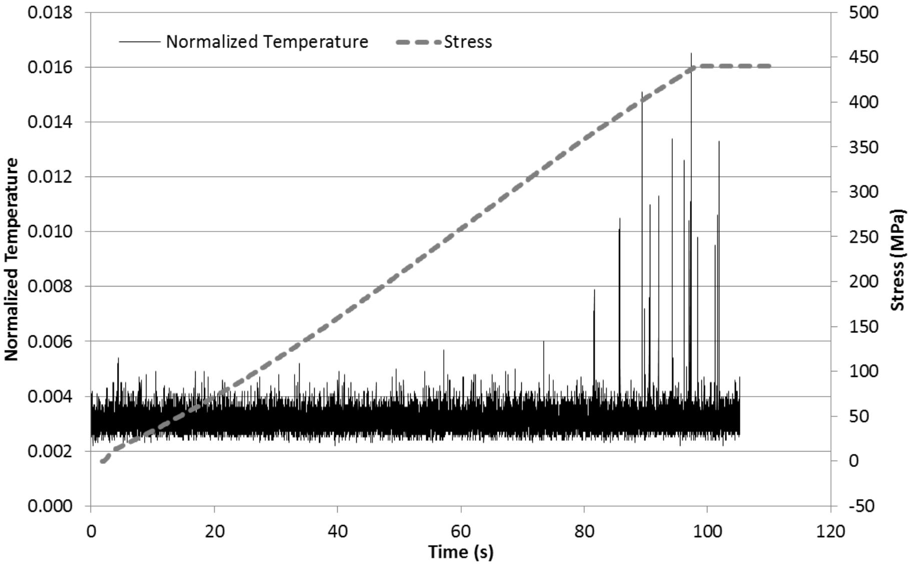

Figure 3. "Timing graph" of the maximum normalized subtracted temperature of the ROI during loading.

A number of 17 indications have been detected during the test, taking a threshold ≥ 0.004 above the average "maximum normalized subtracted temperature" (see Table 1 for quantitative analysis of their magnitude together with test time and respective stress level). Images with visualization of the indications obtained at these specific frames are represented in Figure 4.

Indication (Nr.)	Frame (Nr.)	Time (s)	Load (N)	Stress (MPa)	ΔT (non-dim)	ΔT Cum. (non-dim)
1	12,237	81.580	26,119.15	366.13	0.006	0.006
2	12,245	81.633	26,154.60	366.63	0.008	0.014
3	12,862	85.747	27,496.49	385.44	0.012	0.026
4	12,881	85.873	27,536.13	385.99	0.011	0.037
5	13,421	89.473	28,705.99	402.39	0.017	0.054
6	13,466	89.773	28,766.24	403.23	0.007	0.061
7	13,578	90.520	29,039.53	407.07	0.008	0.069
8	13,604	90.693	29,070.34	407.50	0.011	0.08
9	13,811	92.073	29,510.08	413.66	0.012	0.092
10	14,152	94.347	30,206.50	423.42	0.016	0.108
11	14,445	96.300	30,827.42	432.13	0.011	0.119
12	14,560	97.067	31,056.16	435.33	0.011	0.13
13	14,598	97.320	31,121.71	436.25	0.013	0.143
14	14,772	98.480	31,377.18	439.83	0.009	0.152
15	15,195	101.300	31,385.07	439.94	0.012	0.164
16	15,255	101.700	31,384.88	439.94	0.012	0.176
17	15,280	101.867	31,385.54	439.95	0.014	0.19

Table 1. Summarized indications detected during the loading ramp in tested sample

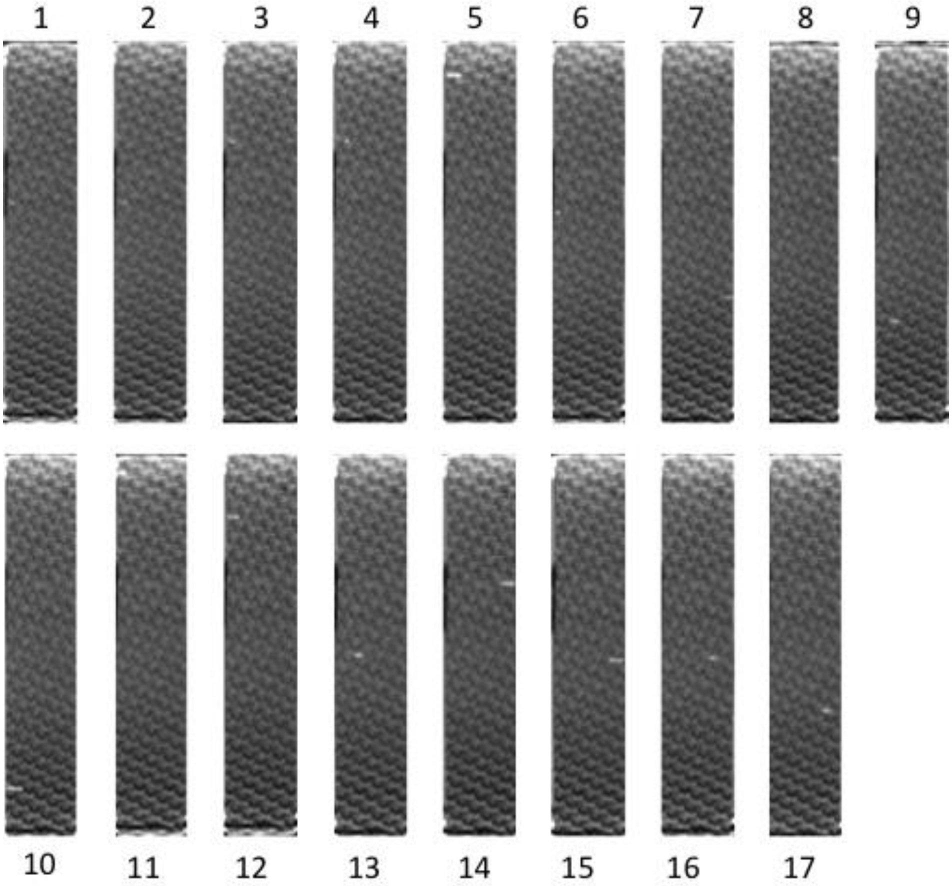

Figure 4. Normalized thermographs from frames showing detected indications (ID number is indicated in each image).

Furthermore, a low pass filter can be used in order to eliminate noise signal before the application of method 1 or 2 for defect detection, which will lead in an easier identification of temperature peaks. A comparison of the “timing graph” recorded at four indications with or without low pass filter application is presented in Figure 5.a and b, respectively. On the other hand, the filter causes a small attenuation of the signal: e.g the amplitude of the normalized temperature recorded for defect 3 is reduced from 0.010 to 0.006 (-40%) after filtering.

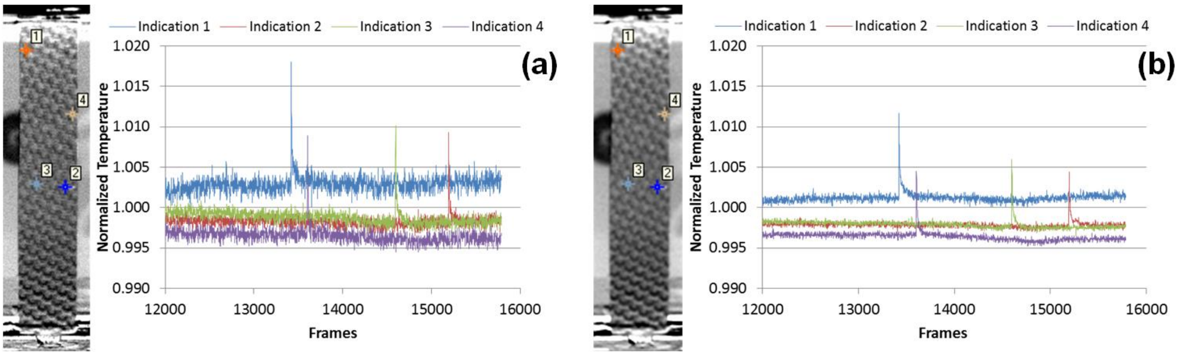

Figure 5. Partial “timing graph” of four individual indications: (a) without and (b) with low pass filter.

4. Conclusions

Passive infrared thermography has reported significant results as a monitoring technique of composite parts under mechanical loading. This technique can provide very useful information in terms of damage occurrence and propagation.

This study has shown the importance of a post-processing in order to eliminate ambient noise from the acquired signal. Two different methodologies have been applied as well as filtering strategy for signal treatment. Once the post-processing has been performed, the automation of the detection process can be easily implemented using numerical software.

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