Inspection of Glass Fiber Reinforced Plastic (GFRP) using Near/Shortwave Infrared and Ultrasound/Optical Excitation Thermography

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ABSTRACT

Glass Fiber Reinforced Plastic (GFRP) is a plastic material reinforced by fine fibers of glass. Various defects may appear when manufacturing this product, i.e. delamination, porosity, undesired inserts, material discontinuity, etc. One of the applications of GFRP is in aerospace industry. In this context, the “Centre Technologique en Aérospatiale (CTA)” provided us with some GFRPs including the aforementioned defects in order to find a non-destructive technique, which has the potential of detecting all of the defects. We used the equipments in our research chair (MiviM) to inspect the specimens with different techniques including Near/Shortwave Infrared, Ultrasound Thermography, and Optical Pulsed/Lock-in Thermography. The experimental results showed that the Near Infrared inspection has the best performance among the other techniques, because of the semi-transparency of GFRP under Near Infrared illumination. Using Near Infrared inspection, we were able to observe all of the aforementioned defects visually, unless the delamination. We also concluded that only the Ultrasound Thermography was capable to detect the delaminations located in the edges. In order to detect the defects automatically, we also suggested an image processing method for image segmentation. We concluded that the thermal photos are much easier than the Near/Shortwave infrared photos to be processed automatically. The reason is that the Near/Shortwave infrared photos provide more details about the inspected material than thermal ones. Those details may be misclassified as defects when using simple image processing algorithms. E.g., the patterns caused by fibers inside the GFRP, which appear only under Near/Shortwave Infrared Illumination, may be misclassified as defect using image processing. In this context, two new image processing techniques with excellent efficiency were also proposed to prevent the mentioned problem.

Keywords: NDT, Ultrasound Thermography (UT), Optical Thermography, Glass Fiber Reinforced Plastic (GFRP), Shortwave Infrared, Near Infrared, Image Processing
INTRODUCTION

Infrared thermography has been used as an outstanding non-destructive testing method. Its basic principle is exciting an object thermally/mechanically and using infrared camera to monitor changes of the object’s surface temperature. Since the subsurface discontinuities may alter the diffusion of the heat, this will affect the thermal distribution of the surface. For stimulation purposes, various excitation sources can be used: cold/hot air, high-powerful lamps and flashes, sonic/ultrasound transducers, eddy current, etc [1]. There are also different heating techniques. Modulated and pulsed heating are among the most popular ones. Step heating (long pulse excitation) is another method in the literature [2]. There are two modes for thermography: 1- The specimen is heated from one side, while thermal data is collected from the same side, i.e. reflection mode; 2- The specimen is heated from one side, while thermal data is collected from the opposite side, i.e. transmission mode. Reflection mode is used when inspecting defects are close to the heated surface, while Transmission is preferred for detection of defects which are closer to the non-heated surface (i.e. deeper defects).

In this paper, three techniques are investigated for thermal inspection. 1- Optical Lock-in Thermography (LT); 2- Optical Pulsed Thermography (PT); 3- Ultrasound Thermography (UT). In optical LT, also known as modulated thermography, absorption of modulated optical radiation results in a temperature modulation that propagates as a thermal wave into the inspected component. As the thermal wave is reflected at the defect boundary, its superposition to the original thermal wave causes changes in amplitude and phase of the response signal at the surface, which are recorded at the same time using an infrared camera. Sinusoidal waves are commonly used, although other periodic waveforms are possible. Sinusoids are more preferable, as the frequency and the shape of the response are preserved (i.e. sinusoidal fidelity); only the amplitude and phase of the wave maybe changed. In optical PT, the specimen surface is submitted to a short heat pulse using a high power optical source. The duration of the pulse may vary from a few ms (~2-15 ms using flashes) to several seconds (using lamps). Absorption of short time pulse energy increases the specimen surface temperature. As time elapses and heating pulse vanishes, the surface temperature will decrease uniformly for a piece without internal flaws. On the contrary, subsurface discontinuities (e.g. porosity, delaminations, disbonds, fiber breakage, inclusions, etc.) will change the diffusion of heat flow and produce abnormal temperature patterns at the surface that can be detected with an IR camera.

Ultrasound thermography (UT), which is also called “vibrothermography”, “sonic IR”, and “thermosonics”, was invented in the end of 70’s, but it was widely used since 90’s. The idea of this method is to induce mechanical waves of high frequency (usually 15~25kHz or 40kHz) into the specimen and to observe the surface temperature changes by infrared camera. This method was successfully applied to detect cracks in metals, delaminations in composite materials, and other defects at both surface and subsurface. It is particularly used in aerospace and automotive industry. In this technique, a short pulse or a sound wave is applied into a specimen. Due to the thermal phenomena, thermoelastic effect, and hysteresis (loss angle), mechanical energy is converted into the thermal waves. Next, the thermal waves travel to the surface. In the vicinity of the defect, the temperature increases and this local increase becomes visible by the IR camera.

In this paper, the aforementioned techniques will be carried out on a few Glass Fibre Reinforced Plastic (GFRP) specimens with various types of defects. The inspection of the specimens will be also studied by using Near/Shortwave Infrared Vision. In order to detect the various types of defects in thermal images automatically, a new image processing technique...
based on Otsu’s threshold selection method is proposed in this paper. For detecting the defects in Near/Shortwave infrared photos, two image processing techniques will be suggested in the following sections as well.

**EXPERIMENTS**

**Optical Thermography**

Acquisition was carried out using an FPA infrared camera (Santa Barbara Focalplane SBF125, 3 to 5 µm), on a 320 by 256 pixel array. Different acquisition frequencies were used in preliminary tests, ranging from 20 to 160 Hz. Two high-power flashes (Balcar FX 60), giving 6.4 kJ for a ~5ms pulse, were used as heating sources in optical pulsed thermography, and two lamps were used as heating source in optical lock-in and long pulse heating (also called step heating) thermography. The excitation frequency used in lock-in thermography was ranging from 0.1Hz to 0.01Hz, and the pulse duration of step heating was 3~5 seconds in inspections. Data was analyzed with PC using MATLAB software. All the specimens were inspected by optical excited thermography using lock-in and pulse heating waveforms. Three specimens with non-uniform structure, bubbles, and without any defect were inspected. No thermal abnormities were appeared on the obtained thermal and phase images for those specimens. A flat bottom hole (FBH) specimen was also made in order to be examined. Figure 1 demonstrates our experimental results for **Optical Lock-in Thermography** of the FBH specimen.

![Fig. 1: LT phasegram with excitation frequency. (a) f=0.1 Hz (b) f=0.01Hz](image)

As it is shown, with the excitation frequency $f=0.1$Hz, the 5 shallower defects (depth from 1 mm to 2.3mm) were detected, while with the excitation frequency of $f=0.01$Hz the probing depth increased, and the two deeper defects (depth=4mm) were detected. Figure 2 demonstrates the experimental results for **Optical Pulsed Thermography (PT)** by using high-power flashes (Balcar FX 60) heating source. As it is illustrated, the deeper or smaller defects are not detected, and the shallow defects are not evident as well. This indicates that the heating energy may be not enough. In order to resolve this problem, the flashes were replaced by lamps, and the heating duration was increased to 3 seconds. Figure 3 shows the test results using long pulse. All the seven defects were detected. The deepest defect is only visualized at low frequency $f=0.02$Hz. After examination of the specimen with FBHs, the specimen with inserts was tested. This specimen is demonstrated in figure 4.
The specimen with inserts

Figure 5 demonstrates the experimental results for LT and PT of the specimen with inserts. As it is demonstrated, three insertions and one defect in the center were detected, which are marked with circles. Moreover, the inspection images show that the left and the right parts of the specimen are obviously different. It should be noted that if the two defects overlap (at the same position, but different depth), then only the defect at the top (closer to the inspected surface) can be detected. This may be why some insertions in the specimen were not detected.
Ultrasound Thermography

After Optical Thermography, Ultrasound thermography (UT) was applied to the specimens. In order to generate mechanical waves, we used an ultrasound set that includes ultrasound generator Branson 2000b, piezoelectric ultrasound converter Branson CR20, two pneumatic cylinders Festo® and booster. For controlling cylinder movement and converter cooling, the pressured air is used. Maximum generated power is 2200W, and main frequencies are 15 kHz, 20kHz, and 25kHz. There is an option of amplitude modulation in the range of 0.1~10Hz or/and frequency modulation up to 100Hz. In UT two configurations have been mainly introduced: 1-Lock-in (modulated) thermography, in which the high frequency signal is amplitude modulated at a much lower frequency; 2-Burst thermography, in which the sample is excited by a brief (typically 50-200 ms) ultrasonic pulse. It is possible to modulate frequency in both configurations. All the specimens were inspected by ultrasound thermography using various modulation frequencies and modulations. The position and number of periods were also changed. Firstly, the specimen with flat bottom holes were examined. The best result was obtained by using a main frequency of 20 kHz and an amplitude modulation of 0.1Hz (Figure 6).

Fig. 5: (a) LT phasegram at $f=0.1$ Hz; (b) PT (long pulse) phasegram at $f=0.14$Hz

Fig. 6: Thermal image (main frequency 20 kHz, amplitude 0~40%, 0.1Hz, 1 period)

After examination of the specimen with FBHs, the specimen with inserts was tested. The best results were obtained for the main frequency of 25 kHz. By changing the parameters of amplitude modulation, and position of the specimen, we got different results. The biggest number of detected inserts was five. The inserts appeared with different contrasts (Figure 7). Different frequencies were examined in this experiment, since the inserts may be at different depths.
As it is evident in figure 7, the triangle on the left-top is clearer with excitation frequency of 0.5Hz than 0.1Hz. By comparing the photos in figure 7, one can notice that the presence of standing waves are more evident at 0.1 Hz. This means that by changing (increasing or decreasing) the mechanical excitation frequency, local thermal gradients appear or disappear at specific resonance frequencies. Observation of the sample from the back side was also implemented in our experiment (Figure 8).

As it is demonstrated in Figure 8, the inserts cannot be seen clearly. This is because they lay deeper from the inspected surface. After examination of the specimen with inserts, the specimens with non-uniform structure and bubbles were examined to detect the delamination. Figure 9 demonstrates these two specimens including delaminations.
As it is shown, two delaminations on the left-top corner are appeared in figure 9-a. The thermal image for the specimen with bubbles is demonstrated in Figure 9-b. As it is illustrated, two delaminations at the right-bottom edge are observed in this figure.

**Near/Shortwave Infrared Inspection**

Two cameras were used for Near/Shortwave Infrared Inspection. First, the Mutech camera operating in Near Infrared spectrum was used. An illuminator operating in 850 nm was also used in order to illuminate the specimens. The specimen was inspected from the backside in which the artifacts could not be detected under visible spectrum, but they could be detected under near infrared illumination because of the glass-fiber semi-transparency in this spectrum. A camera operating in shortwave infrared spectrum designed by Goodrich was also used. The experiments showed that the near infrared gives better discrimination between the inserts and material than shortwave infrared. Figure 10 shows the specimen with inserts, bubbles (porosity) and FBHs in Near Infrared spectrum. As shown, the inspection results are promising for NIR inspection.

![Image of specimen with inserts and bubbles](image1.png)

**Fig. 10:** The frontal view of the specimen with inserts; (b) The backside of the specimen with inserts; (c) The specimen with bubbles; (d) The backside of the specimen with FBHs

**THE IMAGE PROCESSING TECHNIQUES FOR DETECTION OF DEFECTS**

Otsu's Threshold selecting method is a very famous method which is used to automatically perform histogram shape-based image thresholding and producing a binary image. In our researches, we found that Otsu’s method has not a perfect performance for segmentation of the defects in thermal images. For example, figure 11-b shows the effect of Otsu’s method on the thermal image in 11-a.
As demonstrated in figure 11, the Otsu’s method completely detects the very bright parts, but it ignores the defects with lower brightness. The ignored defects are demonstrated in figure 11-a using the red arrows. Therefore, Otsu’s method is not usually ideal for NDT purposes. In order to find a suitable segmentation method in thermal images, we extracted the histograms of different thermal images including some defects, and we noticed that their histograms have generally the same shape of figure 12. E.g., figure 12 shows the histogram of the thermal image demonstrated in figure 11-a.

As demonstrated in figure 12, there is an extremum value at (X=33). Our goal is finding a threshold value between 0 and 255 and converting the original image to a binary image according to the following rule:

\[
I_{\text{Binary}}(n,m)=\begin{cases} 
1(\text{white}) & I(n,m) > \text{Threshold} \\
0(\text{black}) & I(m,n) \leq \text{Threshold}
\end{cases}
\] (1)

In equation 1, \(n\) and \(m\) stand for the indexes of the pixels in the image. The key point behind our segmentation technique is that we supposed that the extremum value in the x axis (X=33 in Fig. 12) is meaningful and it should be the mean value of the intensity of the pixels from class 0 (black pixels in binary image). According to Otsu’s equations [3], the mean value of the pixels...
for each of the two classes, $m_0$ and $m_1$, may be calculated from the original image using the following rules:

$$m_0 = \frac{\sum_{i=0}^{k} p_i}{\sum_{i=0}^{k}} \quad \text{and} \quad m_1 = \frac{\sum_{i=k+1}^{255} p_i}{\sum_{i=k+1}^{255}}$$  \hspace{1cm} (2)

As it is evident from equation 1, for each threshold value ($k$), different binary patterns can be produced, and from equation 2 for each of those binary patterns corresponding to each $k$, different mean values ($m_0$) can be calculated for each of two classes in the binary images. In order to find the best threshold value which correctly segments the defects, firstly we calculate the various mean values of the first class, $m_0$, for each $k$ by changing the value of $k$ from 0 to 255. Next, we choose the threshold value which produces a mean value ($m_0$) nearly equal to the extremum (X=33 in our example). The result of this technique is demonstrated in figure 13. As it is shown, all of the defects have been detected using our proposed technique.

![Fig. 13](image1.png)\hspace{1cm}![Fig. 13](image2.png)

**Fig. 13**: (a) The original image; (b) The segmented image

This technique cannot be used for detecting the defects in Near/Shortwave IR images, because the type and identity of those images is completely different from thermal ones. On the other hand, those images provide much more details about the specimens (e.g. the fibers) which may be misclassified as defect. In order to detect the bubbles and inserts in near infrared photos automatically, we proposed two new image processing techniques. Figures 14 and 15 show the block diagram of our algorithms. Our proposed technique’s results for the specimens with bubbles and inserts are shown in figure 16.

![Fig.14](image3.png)\hspace{1cm}![Fig.15](image4.png)

**Fig.14**: The block diagram of our suggested algorithm to detect the inserted shapes

**Fig. 15**: The block diagram of our suggested algorithm to detect the bubbles
CONCLUSIONS

In this paper, thermal and near/shortwave Infrared inspection of Glass Fiber Reinforced Plastic (GFRP) was studied. In the thermal inspection part of the experiments, optical and ultrasound thermography with pulsed and lock-in heating techniques were examined. We obtained excellent inspection result for the flat-bottom hole specimen with probing depth of up to 4-5mm using long pulsed (step) and lock-in optical thermography. However, long pulsed thermography is more preferable in our experiments since inspection is faster by optical pulsed IRT than lock-in IRT. Our experimental results also showed that NIR inspection of the specimen with flat bottom holes have excellent efficiency as well. The ultrasound technique is capable to detect some of the flat bottom holes. For the specimen with inserts, only four inserts were detected by optical thermography. Ultrasound thermography (UT) showed much better result than optical thermography to detect the inserts. By changing the main frequency, the excitation mode and the position of the horn, one can obtain more detailed information about the defects in UT. For example, to detect discontinuities in higher depth of the structure, lower frequencies should be applied. The problem with ultrasound thermography is that it is not capable to detect all the inserts together in the same trial. For the specimen with inserts, NIR inspection showed the best results. For the specimen with bubbles (porosity), we concluded that none of the optical and ultrasound thermography are suitable for detecting the subsurface bubbles, while NIR inspection showed excellent results. Among methods used in this investigation, ultrasound thermography was the only method that allowed detecting the delaminations. In general, we concluded that NIR inspection has much better performance than ultrasound and optical excited thermography, unless for the case of the delamination. We also concluded that the thermal photos are much easier than the Near/Shortwave infrared photos to be processed automatically. The reason is that the Near/Shortwave infrared photos provide more details about the inspected material than thermal ones. Those details may be misclassified as defects when using simple image processing algorithms.

REFERENCES


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