Delamination detection and impact damage assessment of GLARE by active thermography

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Abstract

GLARE (GLAss REinforced) is a Fibre Metal Laminate (FML) consisting of alternating layers of thin aluminium and glass fibre reinforced prepregs, whose improved physical properties confer it an interesting advantage over aluminium and composite materials for a number of aerospace applications. On the other hand, contrary to monolithic structures, GLARE can suffer from internal damage either during fabrication or in-serve stages. Non-destructive testing and evaluation (NDT&E) of GLARE is still a challenge, especially considering that large structures are typically sought (*e.g.* aircraft fuselage). In this paper, we investigated the use of infrared thermography for the inspection of GLARE. The experimental results presented herein demonstrate that is possible to detect delamination-type defects and to assess the impact severity on GLARE through active thermography techniques, specifically pulsed thermography and vibrothermography. C-scan ultrasonic testing was performed as well with the intention of providing supplementary results

Keywords: active thermography, GLARE composites, fibre metal laminates, pulsed thermography, vibrothermography, C-scan ultrasounds, impact damage, delaminations.

1. Introduction

GLARE is a hybrid material from the family of the Fibre Metal Laminates (FML), which consist of alternating layers of thin metal (*e.g.* aluminium) sheets (0.3–0.5 mm thick) and glass fibre reinforced prepregs (0.25–0.5 mm thick). This configuration provides very good fatigue properties, good impact, damage tolerance and fire resistance characteristics. The main approach for developing GLARE composites includes the placement of layers from aluminium alloy(s) and the prepregs between them in a specific base. After this, the multi-layer structure is placed in an autoclave for approximately 2 hours at a temperature of 120°C and 6 bar pressure. The aluminium layers have a maximum of 1.65 m of wideness. This results to a problem as far as the manufacturing of large structures of the aircraft is concerned (*i.e.* > 2 m). To overcome this, the development of consecutive aluminium alloy layers (next to each other) leaving a very small gap in between them (~ 1 mm) has been used. This approach is also known as GLARE *splicing method*. Nonetheless, rapid delamination was observed, especially during the loading of such structures in more than 400 MPa. For this reason, the *self-forming technique* was developed. During this technique, due to the pressure that is applied at the doublers (*i.e.* placed aluminium alloy sheets) in the autoclave and because of the use of the adhesive for the preparation of the prepregs, the voids are filled from the material itself. The composite has now improved strength and the filled gaps are no longer the weak spots of the material.

The prerequisite for more competent and cost effective aircraft has led to the evolution of innovative testing and evaluation procedures. Non-destructive testing and evaluation (NDT&E) techniques for assessing the integrity of an aircraft structure are essential to both reduce manufacturing costs and out of service time of aircraft due to maintenance. In literature, one can find C–scan ultrasonics inspection [1] on composite structures from GLARE. Furthermore, x-rays radiography [2] has been used in the inspection of GLARE in specific situations, such as preliminary detection of cracks in the aluminium part of the material. Eddy Current testing [3] has also been applied, providing good results for detection

on the surface and near surface defects. The main limitation of this approach is detecting defects at the greater depths within the material. Furthermore, infrared thermography [4] has also found use in the inspection of joints from GLARE composites. Nowadays, active thermography thermal NDT&E is commonly used for assessing aircraft composites. The active thermography approach is explained next.

2. Active thermography

Infrared thermography is an NDT&E technique allowing fast inspection of large surfaces [5]. There are different active techniques depending on the stimulation source [6]: pulsed thermography (PT), step thermography (ST), lock-in thermography (LT) and vibrothermography (VT), to name the most popular. Data acquisition is carried out as depicted in Figure 1.

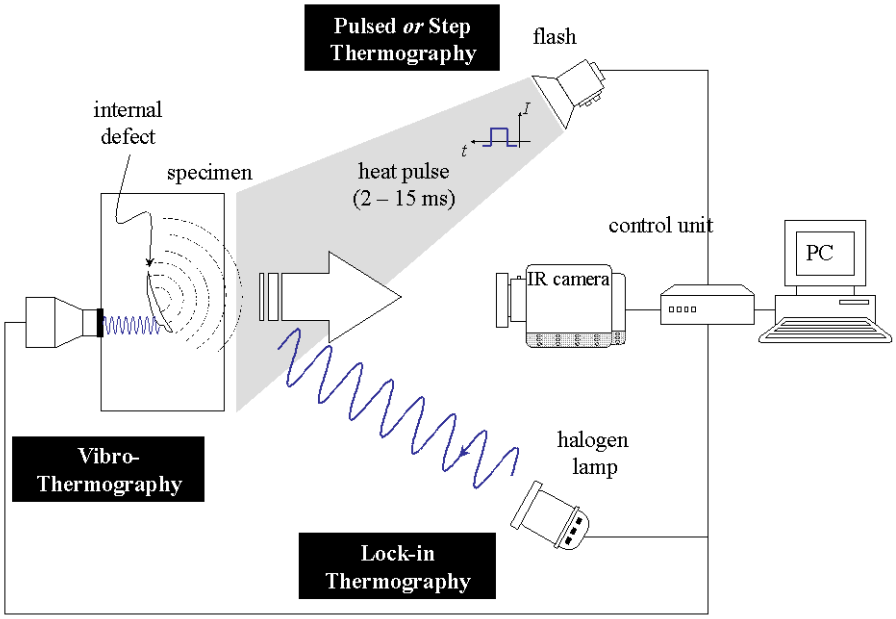


Figure 1. Schematization of the data acquisition and processing by PT.

The specimen is stimulated with an energy source, which can be of many types, such as *optical*, *mechanical* or *electromagnetic*. Optical energy is normally delivered *externally*, *i.e.* heat is produced at the surface of the specimen from where it travels trough the specimen to the subsurface anomally (defect) and back to the surface. Mechanical energy on the other hand, can be considered as an *internal* way of stimulation, since heat is generated at the defect interface and then travels to the surface. Moreover, energy may be delivered in *transitory* or *steady state* regime, in either *transmission* or *reflection* mode depending on the application. For instances, pulsed thermography, which is typically performed using a heat pulse of a few milliseconds can be considered as an optical-external technique in transitory regime and in reflection mode. Regardless of the technique used to stimulate the specimen, the thermal signatures can be visualized at the surface using an infrared camera. A thermal map of the surface or a *thermogram* is recorded at regular time intervals.

A wide variety of methods coming from the field of machine vision [7] have been adapted for NDT applications and are discussed in detail elsewhere [8], [9], [10]. Next section presents the experimental procedures used in the present investigation.

3. Experimental procedures and techniques

Firstly, GLARE composites were prepared with different inserts for simulating delamination in the samples. Table 1 describes the first set of samples, which were prepared using aluminium 2024-T3 of

0.4 mm thickness and BR-127 chromic anodising as surface preparation on the material. The defects were either from Teflon® or polyamide, the dimensions and specifications of all investigated samples can be seen in the schematic of Figure 2a.

Table 1. Description of GLARE composites

Sample	GLARE type	Composite Orientation	Lay-up	Dimensions Length (mm)	Dimensions Width (mm)
DT1	G.e-g/w-2/1-0.4	e-Glass MMR–002/w	Al/FM-73/e-Glass/FM-73/Al	150	50
DP2	G.e-g/w-2/1-0.4	e-Glass MMR–002/w	Al/FM-73/e-Glass/FM-73/Al	150	50
DT3	G.Bor-2/1-0.4	Boron 5521/un	Al/FM-73/Boron/FM-73/Al	150	50
DP4	G.Bor-2/1-0.4	Boron 5521/un	Al/FM-73/Boron/FM-73/Al	150	50
DT5	G.e-g/w-3/2-0.4	e-Glass MMR–002/w	Al/FM-73/e-Glass/FM-73/Al/ FM-73/e-Glass/FM-73/Al	150	50
DP6	G.e-g/w-3/2-0.4	e-Glass MMR–002/w	Al/FM-73/e-Glass/FM-73/Al/ FM-73/e-Glass/FM-73/Al	150	50
DT7	G.Bor-3/2-0.4	Boron 5521/un-un	Al/FM-73/Boron/FM-73/Al/ FM-73/Boron/FM-73/Al	150	50
DP8	G.Bor-3/2-0.4	Boron 5521/un-un	Al/FM-73/Boron/FM-73/Al/ FM-73/Boron/FM-73/Al	150	50

Secondly, a GLARE specimen (Al/0°/90°/0°/Al/0°/90°/0°/Al/0°/90°/0°/Al, using unidirectional glass-fibre epoxy layer FM94S2) was fabricated with simulated delaminations of four kinds: 1-ply film release, 2-plies film release, Kapton®/Frekote® inserts and aluminium shim/Frekote® inserts. The specifications for this plate are shown in Figure 2b.

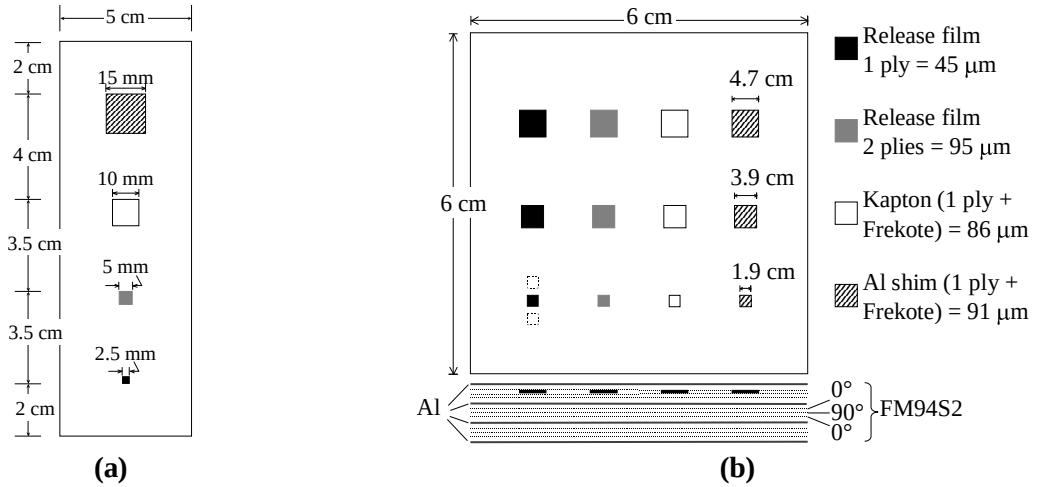


Figure 2. Schematic of investigated samples containing inserts: (a) DT and DP type specimens, and (b) specimen GLARE013.

And lastly, 12 GLARE composites, using s-Glass instead of e-Glass, were prepared for impact damage testing; 6 with Al/FM-94/s-Glass/FM-94/Al and the other 6 with Al/FM94/s-Glass/FM94/Al/FM-94/s-Glass/FM94/Al, see Table 2. In the instance of the impact damage testing [11], a falling weight impact tester was used. A lead filled tube with a standard hemispherical 8 mm diameter steel ball was used as the impacter. A sliding plate at the base of the guiding tower allows the impacter tube to be caught after impact to prevent secondary impact of the sample. The impact energy was calculated using the standard equation: $E = mgh$, where: m is the mass of the impacter, g is the acceleration due to gravity (9.81 m/s) and h is the height from which the weigh was dropped. The following impact energies were calculated: 2, 4 and 8 J, as indicated in Table 2.

Table 2. Description of GLARE type composites

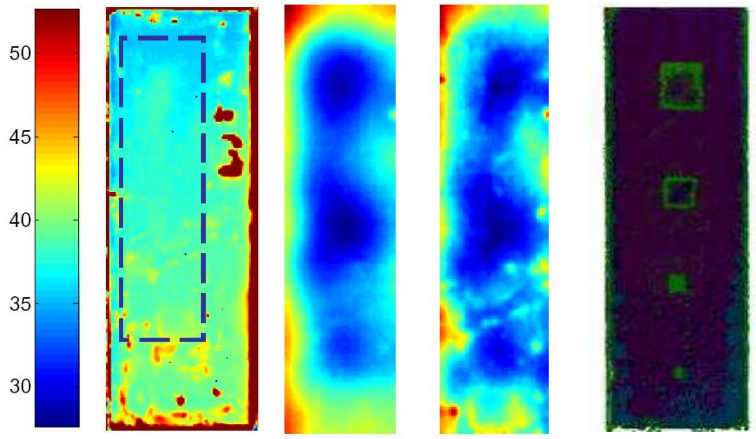
Specimen	Impact energy [J]	Lay-up
Glare001	2	Al/FM-94/s-Glass/FM-94/Al/FM-94/s-Glass/FM-94/Al
Glare002	4	Al/FM-94/s-Glass/FM-94/Al/FM-94/s-Glass/FM-94/Al
Glare003	2	Al/FM-94/s-Glass/FM-94/Al
Glare004	4	Al/FM-94/s-Glass/FM-94/Al
Glare005	2	Al/FM-94/s-Glass/FM-94/Al
Glare006	8	Al/FM-94/s-Glass/FM-94/Al
Glare007	8	Al/FM-94/s-Glass/FM-94/Al/FM-94/s-Glass/FM-94/Al
Glare008	8	Al/FM-94/s-Glass/FM-94/Al
Glare009	8	Al/FM-94/s-Glass/FM-94/Al/FM-94/s-Glass/FM-94/Al
Glare010	4	Al/FM-94/s-Glass/FM-94/Al
Glare011	4	Al/FM-94/s-Glass/FM-94/Al/FM-94/s-Glass/FM-94/Al
Glare012	2	Al/FM-94/s-Glass/FM-94/Al/FM-94/s-Glass/FM-94/Al

In the investigation of the inserts, acquisition was carried out using either a Santa Barbara Focal Plane SBF125camera (14 bits, InSb 320x256 FPA, 3 - 5 μm, nitrogen-cooled) or a ThermaCAM™ Phoenix® from FLIR Systems (14 bits, InSb 640x512 FPA, 3 - 5 μm, Stirling closed cycle cooler). Two high power flashes (Balcar FX 60), providing 6.4 KJ for 2 - 10 ms each, were used as heating sources. For the case of vibrothermography inspection, a transducer working at 20 kHz was used as an ultrasound source. Thermographic data was analyzed with a PC (Pentium 4, 2 GB RAM) using MATLAB® language from The MathWorks, Inc. In the investigation of the impact damaged samples, a pulsed thermographic system (Echotherm) employing a medium wave (3 to 5 μm) infrared camera (Phoenix) was used for the imaging and analysis of the panels. Echotherm, a portable state-of-the-art non-destructive testing and evaluation system, has an attached integrated flash heating system (giving ~10 KJ for variable duration of the flash heating - up to 25 ms). The Phoenix mid-wave infrared camera (also attached to the system) uses a cooled InSb detector with a maximum frame rate of 60 Hz and a focal plane array pixel format of 320x256. Furthermore, C-scan ultrasonic immersion testing was used with the intention of providing supplementary information about the defects.

4. Results and discussion

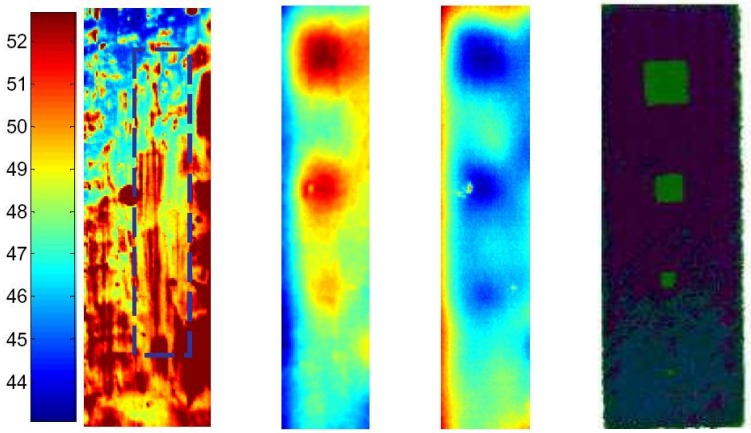
In the investigation of composites with active thermographic approaches, since the thermal diffusivity mainly affects the time of maximum thermal contrast, the clearest images (high thermal contrast between defect and sound area) are acquired at relatively long periods during the cooling down thermal transient process. In the instance of the inserts, detection of the simulated delamination for specimens DT1 and DP2 can be seen in Figure 3 and Figure 4, respectively. Furthermore, supplementary C-scan results can also be seen for both samples as indicated in these figures. It is possible to detect the 3 largest inserts by infrared thermography. Defect contrast is better for polyamide inclusions (specimen DP2) than for Teflon® inserts (specimen DT1). All defects are seen on the C-scan images for both specimens.

In the case of specimen GLARE013, All defects can be seen by pulsed thermography (Figure 5a) with data processed by TSR [12] (first time derivative), and most of them can be detected by VT (Figure 5b). However, is more difficult to differentiate between materials from the VT results than by PT. Aluminum inserts in particular have a distinctive signature with inverted sign as can be seen. An additional defect can be seen in the first column of defects (1-ply film release). These defect was not included on the specimen specifications from the manufacturer. C-scan results (Figure 5c) confirm the existence of this defect.



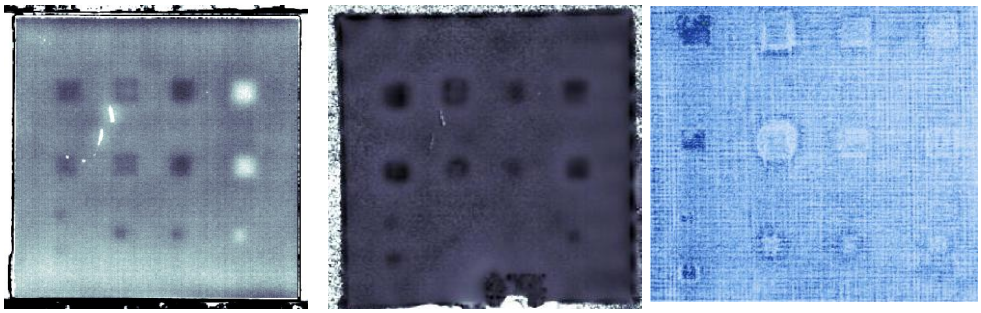
(a) **(b)** **(c)** **(d)**

Figure 3. Results for specimen DT1: (a) raw thermogram at t = 0.02 s, (b) 2nd time derivative image of the selected area at t = 0.6 s, and (c) phasegrams obtained by pulsed phase thermogram at f = 0.8 Hz.



(a) **(b)** **(c)** **(d)**

Figure 4. Results for specimen DP2: (a) raw thermogram at t = 0.02 s, (b) 2nd time derivative image of the selected area at t = 0.06 s, and (c) phasegrams obtained by pulsed phase thermogram at f = 1 Hz.

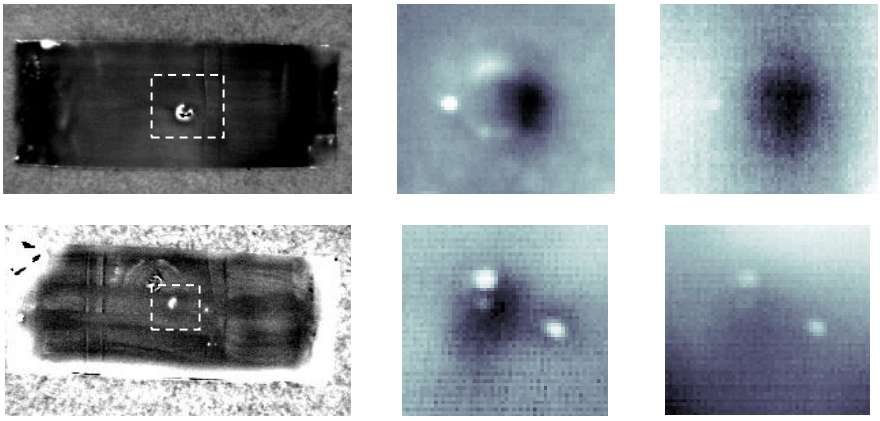


(a) **(b)** **(c)**

Figure 5. (a) first derivative image at t = 0.6 s, (b) vibrothermography result, and (c) C-scan ultrasounds (15 MHz).

In the case of the assessment of the impact-damaged samples, it was possible to view the impact damage on the surface, especially in the case of the thinner composite panels such as specimen GLARE006 (Figure 6, top). Furthermore, even in the case of the thicker samples as specimen GLARE007 (Figure 6, bottom) the defected areas, created by the impact damage testing, could be picked up by pulsed

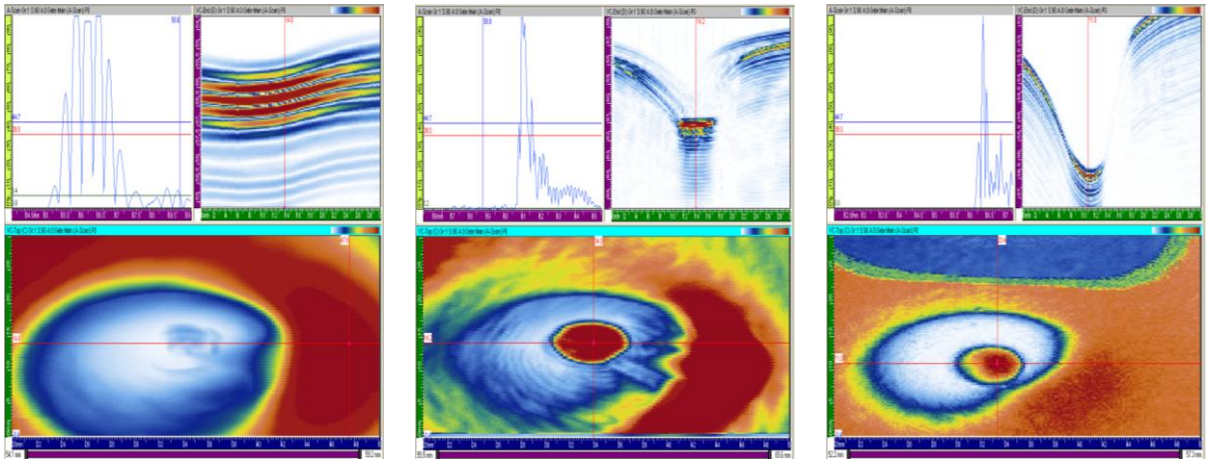
thermography as can be seen in Figure 6a. Processing results by pulsed phase thermography [13] improve defect contrast and provides an indication about the extent of the internal damage. In accordance with the phase probing properties [14], the phasegrams at 1 Hz (Figure 6b) provide information about deeper features than the phasegrams at 0.15 Hz. It can be observed from these results that the extend of damage is greater, for the case of a thin plate subjected to a high energy impact (8 J) than for a thick plate subjected to a lower impact energy (4 J), as expected.



(a) **(b)** **(c)**

Figure 6. Results for specimens GLARE006 (top) and GLARE007 (bottom) after impact damage testing using 8 and 4 J, respectively: (a) thermogram, and the corresponding phasegrams of the cropped portion obtained by PPT at f =(b) 1 and (c) 0.15 Hz.

Ultrasonic A-B-C-scan results for specimen GLARE006 are shown in Figure 7 for three ultrasound frequencies, as indicated. From these results it can be seen that is difficult to get a signal from the second aluminium layer since glass fibres reflect back ultrasound waves and hinder the visibility of the subsequent aluminium layers.



(a) **(b)** **(c)**

Figure 7. Ultrasonic testing results for specimen GLARE006: (a) 5, (b) 10 and (c) 15 MHz.

Conclusions

The main objective of this work was to employ active thermography approaches such as pulsed thermography and vibrothermography in order to detect simulated delamination (inserts), as well as impact damage on GLARE composite panels. Both approaches were mostly used [15] in qualitative terms (*i.e.* defect detection). The acquisition of the thermograms was completed taking into consideration the thermal characteristics of the composites under investigation, as well as the defect type

(*i.e.* impact damage or delamination). In both situations thermography proved to be an appropriate means of revealing-detecting the defects at the investigated composite panels. From the obtained results it was realised that thermography was possible to detect the defected areas in the GLARE composite panels that were investigated in this work. Processed results showed that is possible to differentiate between dissimilar materials in case of delamination-like inserts and to provide an indication of the damage severity from impacted specimens. It is therefore concluded that thermography could be used in the rapid investigation of GLARE composites, producing interpretable results.

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