On the use of infrared thermography as NDT of aerospace materials

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Abstract: *Aeronautical structures are manufactured in a large range of materials like metallic, plastic or composite. The maintenance of aerospace structures consists in conventional inspections using different Non-Destructive Evaluation (NDE) methods in order to maximize the structure life and safety. LEISC (Laboratory for Integrity Evaluation of Composite Structures) from the POLITEHNICA University of Bucharest is currently developing NDE methods based on the ultrasonic guided Lamb waves propagation and on the infrared thermography (IRT), methods also adapted for composite and sandwich structures. The present study focuses on the aid provided by the infrared thermography for non-destructive evaluation of aerospace materials and structures. Several samples were manufactured and tested. They consist in different materials employed in aerospace structures (metals, plexiglass, composites, hybrid composites, sandwiches) and include the most commonly encountered kinds of damages (inclusions, loss of material, delaminations, impact damages). Some results concerning the use of the Infrared Thermography (IRT) for monitoring the integrity of different type of materials used in aerospace structures are presented. Both passive and active thermography applications with illustrative examples are considered.*

Key Words: NDE, NDT, Infrared Thermography, Aerospace Materials

1. INTRODUCTION

In the design *fail safe* or *damage tolerant* philosophies, an important role is played by the material characteristics and state. The materials must have superior mechanical, physical, and chemical properties. Static strength and stiffness or other fatigue, impact and damage resistance, corrosion and wear resistance are very important characteristics. A material should also be light and therefore, the stiffness to weight ratio or strength to weight ratio are design targets. Nowadays, together with advanced aluminium or steel alloys, aerospace structures are manufactured as well in composites as glass reinforced fibres composites(GFRP), carbon reinforced fibre composites (CFRP), or hybrid composites (Fibre Reinforced Metal Laminates, FRML). The current trend is focused on the replacement of the homogeneous materials by the composites and multi-materials. For instance, composite parts are nowadays increasingly used on modern aircraft including safety critical primary structures. For example in the Boeing's 7E7 Dreamliner project 50 % of its structure is made of FRML. In the Airbus 380, the percent of composites (including Glare type FRML) is around 25 %.

The development of new materials requires the availability of effective non-destructive techniques able to highlight damages at an incipient stage, during manufacturing or in service. The NDE process needs low cost methods and devices having great reliability and sensitivity, user friendliness at high operational speed in order to answer to increasingly complex materials and structures. The Infrared thermography (IRT) seems attractive because of its non-contact character and two-dimensionality, which allows for a relative fast control in service, inspections of large areas, [1-4]. The present study focuses especially on the aid provided by active (Lockin and Pulse) Thermography) for NDE of aerospace materials and structures. The experimental analysis was performed in our laboratory by considering several specimens made of materials effectively employed in aircraft fabrication (metals, composites, hybrid composites, sandwiches) and which included several kinds of damage most commonly encountered (delaminations, impact damages, non-uniformities).

The term damage can be defined as changes produced into a system that adversely affect its performance. This definition implyies a comparison between two different states of the system: the initial one or undamaged state and a damaged one. In the IRT method a damaged area has a different colour appearance with respect to surrounding sound area, representing a hot spot or a cold spot in a thermogram.

2. DESCRIPTION OF THE EXPERIMENTAL SETUP

Thermographic methods are based on the emission of infrared radiation by the surface of the object under investigation. Infrared cameras do not see temperatures, they detect thermal radiation giving an image of the temperature distribution associated with the object. Infrared Thermography can be considered a non-contact and global method as relative large areas of the order of 1-2 m^2 can be monitored.

There are two main approaches that can be used: passive and active. The passive one is appropriate for use when the investigated sample has different temperature with respect to the ambient. The active methods are the Pulse/Flash Thermography, Lockin Thermography and Vibrothermography. In the Pulse Thermography (PT) the heating process consists in a constant flux during several seconds to tens of seconds. The flash thermography, used especially for metallic structures uses higher thermal loads obtained by flash injection of heat of typically 10 ms. The decay of the surface temperature is then recorded and analysed (fig. 1).

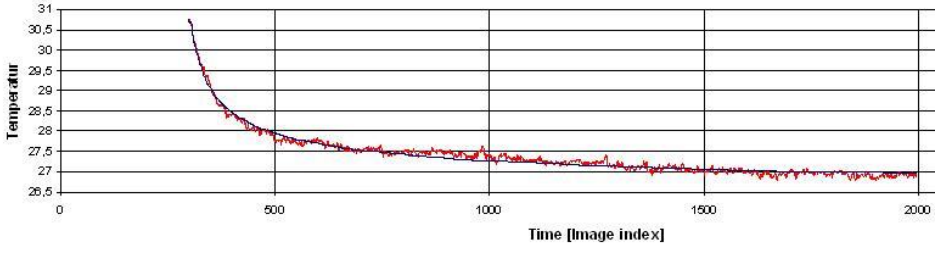


Fig. 1 Temperature in a target point of a sample for the case of PT

Less thermal load uses Lockin thermography (LT), the heating being performed in a sinusoidal way, (fig. 2). In LT, the thermal waves generated at the surface propagate inside the material by diffusion. Some losses by radiation and convection are also present.

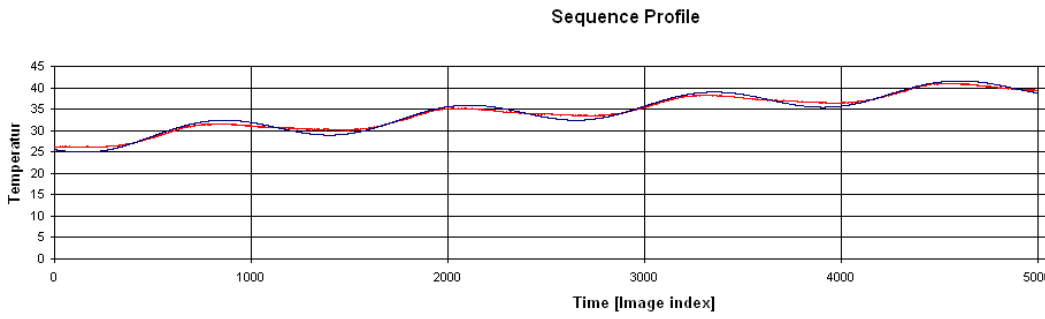


Fig. 2 Temperature in a target point of a sample for the case of LT

This wave will be reflected by damages as voids, delaminations etc. The presence of a damage influences the diffusion rate, the damage areas appearing as areas of different temperature with respect to the surrounding sound areas.

The integrated system used for active IRT contains an excitation source (power electronics module and a panel with 4 halogen lamps -actual power 2.6 kW). In the case of the Flash Thermography, a Hensel generator of 6 kJ is utilized. The power electronics module with the IR-NDT software and IRX-box control the lamp panel according to chosen parameters (see fig. 3). IR-NDT, shown in [5], is an advanced software containing various functions for an easy, versatile use.

Fig. 3 Basic setup for Active Infrared Thermography

The non-linear electrical signal for the modulation of the heat source is generated by IRX-box of the system. The modulation signal controls the power electronics and thus the power output of the heat source.

The basic properties involved in the NDE of a material are: k – thermal conductivity [W/m/K], ρ – density [kg/m^3] and c – specific heat capacity [J/kg/K)]. Other interesting thermal property are: $\alpha = k/\rho/c$ – thermal diffusivity and $e = (k\rho c)^{1/2}$ – thermal effusivity. The thermal diffusivity is a measure of the material's ability to conduct heat versus its capacity to store it. The thermal effusivity measures the material's ability to exchange heat with its

surroundings. In Table 1 the principal properties (indicative) of the materials tested in this paper are given.

Table 1. Thermal properties of the tested materials

Material	Density [kg/m^3]	Specific heat [J/kg °K]	Conductivity k[W/(m °K)]	Diffusivity α [m^2/s 10^{-7}]	Efussivity e [Ws$^{0.5}$/(m^2 °K)]
Aluminium	2702	903	237	947	24047
Plexiglass	1200	1470	0.19	1.13	
CFRP (II)	1600	1200	7	36.458	3666.1
CFRP (⊥)	1600	1200	0.8	4.167	1239.3
GFRP(II)	1900	1200	0.38	1.667	930.8
GFRP(⊥)	1900	1200	0.3	1.316	827.0
Epoxy	1150	1100	0.45	1.372	525.3

In the case of Lockin Thermography, the penetration depth which is a characteristic length given by $\mu = \sqrt{2\alpha/\omega}$ depends on α, the thermal diffusivity [m^2/s] and ω, the modulation circular frequency [rad/s]. If the thermal characteristics of the specimen are unknown, one can try different stimulation frequencies. The used Flir A 40 M camera works in the spectral range 7.5-13 μm and has a good thermal resolution: 0,08ºC. It can be used in three standard temperature ranges -10°C to 55°C, -40ºC to +120ºC or 0ºC to +500ºC, [6,7].

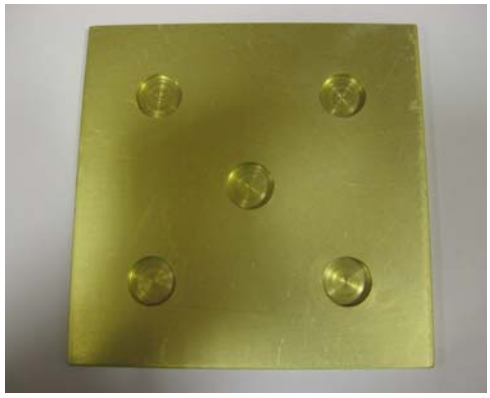
In aeronautics, IRT are used especially for: localisation of delaminations and disbondings of composite structures**,** control of the water infiltration in sandwich structures, control surfaces, radoms etc. Other applications concern the diagnosis of the bracket systems and tire; diagnosis of the degivration systems; identification of cracks and corrosion, power systems examination etc.

3. RESULTS FOR ISOTROPIC MATERIALS

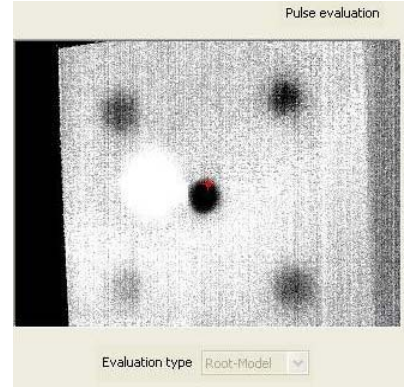
For the evaluation of the metallic samples a powerful heating source and a short pulse thermography (or FT- flash thermography, [8]) are utilized. A first example consists in an aluminium plate with five flat-bottom circular holes of same diameters and different depths (figure 4 a). The parameters for the flash thermography are: excitation period - 10 [s] and pulse-length - 15 ms. Using a camera frequency image acquisition of 50 Hz one obtains a total number of 500 images. The figure 4 b presents a corresponding thermogram for this plate obtained with the root-model (first derivative).

Another example consists in a sandwich plate with nine flat-bottom circular holes of same diameters and different depths (figure 5 a). The parameters for the flash thermography are: excitation period - 10 [s], pulse-length – 2 ms. Using a camera frequency image acquisition of 50 Hz one obtains a total number of 500 images. The figure 5 b presents the corresponding thermogram obtained also using the root-model (first derivative).

In both cases the examination was performed on the undamaged face of the plate. The FT method gives good results for this types of isotropic materials, the specific advantage being the very short time of heating and analysis.

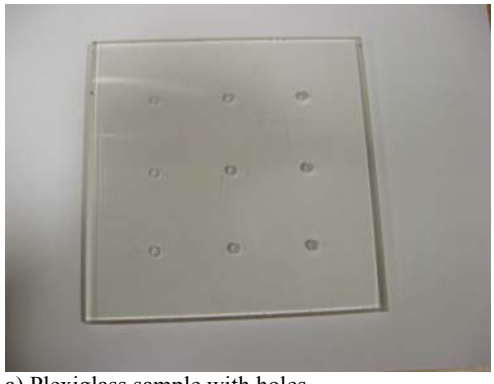


a) Aluminium sample with holes

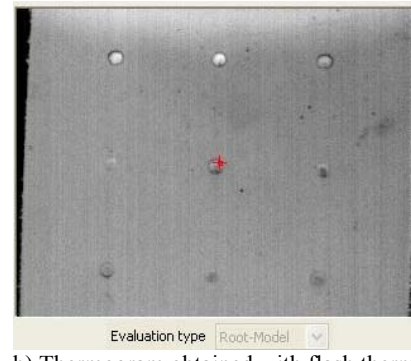


b) Thermogram obtained with flash thermography

Fig. 4 Aluminium plate with five flat-bottom circular holes and a corresponding thermogram



a) Plexiglass sample with holes



b) Thermogram obtained with flash thermography

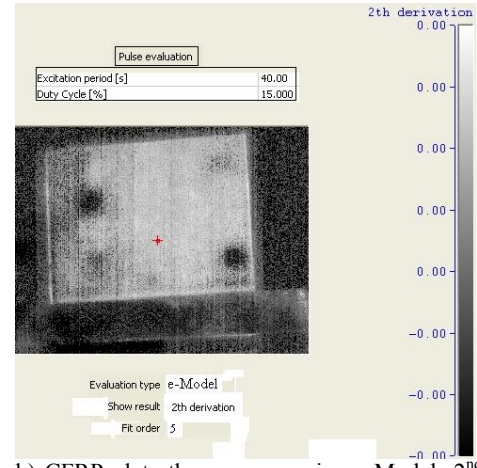
Fig. 5 Plexiglass plate with nine flat-bottom circular holes and a corresponding thermogram

4. RESULTS FOR COMPOSITE AND SANDWICH STRUCTURES

A first composite sample consists in a carbon fibre reinforced plastic (CFRP) 300×300 mm plate with delaminations. The figure 6 presents this plate and a corresponding thermogram (using Pulse Thermography -PT) with the following test parameters: the excitation period - 40 [s], duty cycle - 15 [%], amplitude low - 0 [%], amplitude high - 100 [%], acquisition duration 40 [s]. The camera frequency image acquisition is of 50 Hz, resulting a total number of 2000 images, [9]. The thermogram shown in Figure 6b, highlights four regions of delamination, two of them being more close to the examined surface.

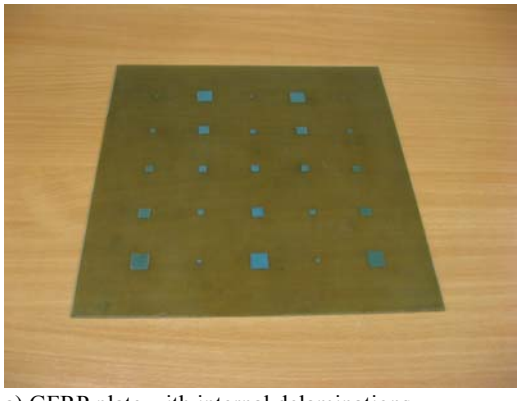
The second sample configuration is a glass fibre reinforced plastic (GFRP) specimen which is fabricated utilizing different inserts during the manufacturing process, with frictionless thin sheets in order to simulate the delamination. The specimen, similar to the one used in [3] has a size of 300×300 mm and 10 layers. The thickness of each layer was approximately of 0.25 mm (total thickness 2.5 mm). Defect sizes of 3×3, 5×5, 7×7,10×10, and 15×10 mm were inserted at different depths**.** No surface painting has been used prior to the inspection using LT. Figure 7b shows a thermogram obtained using LT with the following parameters: period 25s (frequency =0.04Hz), total time of the test 100 s (4 periods) with a camera frequency image acquisition of 25 Hz, obtaining 2500 images, [10].

a) CFRP plate with internal delaminations

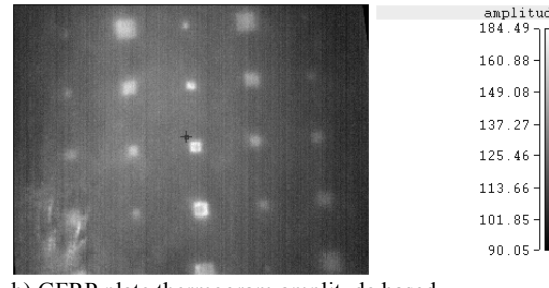


b) CFRP plate thermogram using e-Model -2nd derivative

Fig. 6 CFRP plate with internal delaminations and a corresponding thermogram



a) GFRP plate with internal delaminations



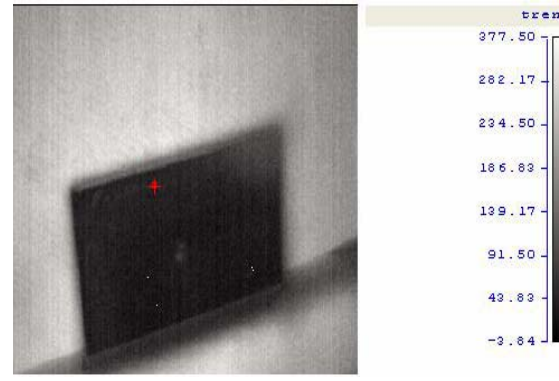
b) GFRP plate thermogram amplitude based

Fig. 7 GFRP plate with internal delaminations and a corresponding thermogram

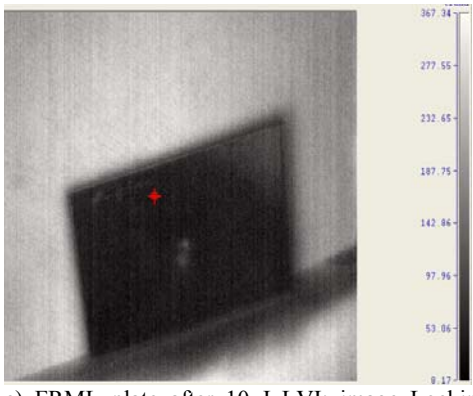
According to their thermal properties, for composite materials based on glass or carbon fibres, active PT or LT represent a more adequate technique, able to detect small size delaminations if they are close to the examined face of the damaged plate.

Other examples concern several FRML samples [11], consisting in 5 layers (3 Aluminium layers and 2 CFRP layers), inspected after they have been tested at low velocity impact (LVI). The samples have been painted in black prior to the inspection using LT. The parameters of the examinations were: period 20s (frequency =0.05Hz), total time of the test 100 s (4 periods) with a camera frequency image acquisition of 50 Hz, obtaining 4000 images. Results are shown in Figure 8.

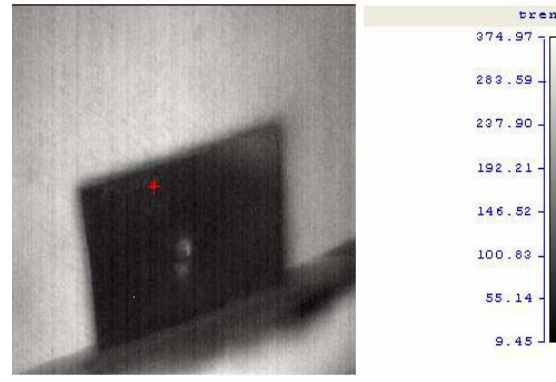
a) FRML plates



b) FRML plate after 5 J LVI: image Lockin -harmonic approximation (time)-trend



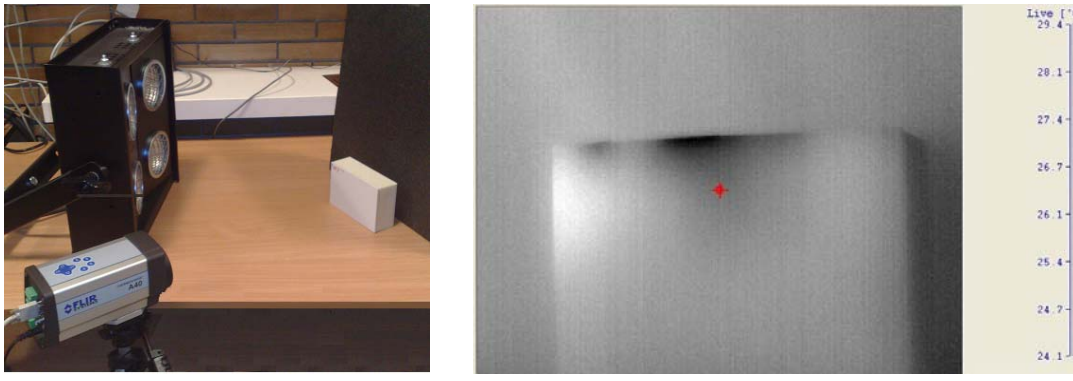
c) FRML plate after 10 J LVI: image Lockin -harmonic approximation (time)-trend



d) FRML plate after 15 J LVI: image Lockin -harmonic approximation (time)-trend

Fig. 8 FRML plates inspected after low velocity impact tests

The detection of water ingression, as for example the detection of moisture penetrated in aircraft structures represents a specific application of IRT for sandwich structure. In this case, no always active techniques are necessary in order to highlight the usually cold spot due to the water presence, in any form. The example sample is a 15 cm x 10 cm x 5 cm sandwich type plate with faces in composite GFRP (4 layers of a total thickness 2 mm) and polyurethane foam core, 46 mm thick (fig. 9a). Some cold water was injected in the space between the upper face and core, [12]. Using the infrared camera, a live view of the plate is presented in Figure 9b. The lowest temperature is in the region with the water ingression and the hot spot is due to the reflexion of a heating lamp. One can also use the active thermography. Some local changes concerning the heat transfer characteristics of a sandwich plate can occur at the surface temperature distribution during cooling or heating, which may highlight the presence of water within the core.

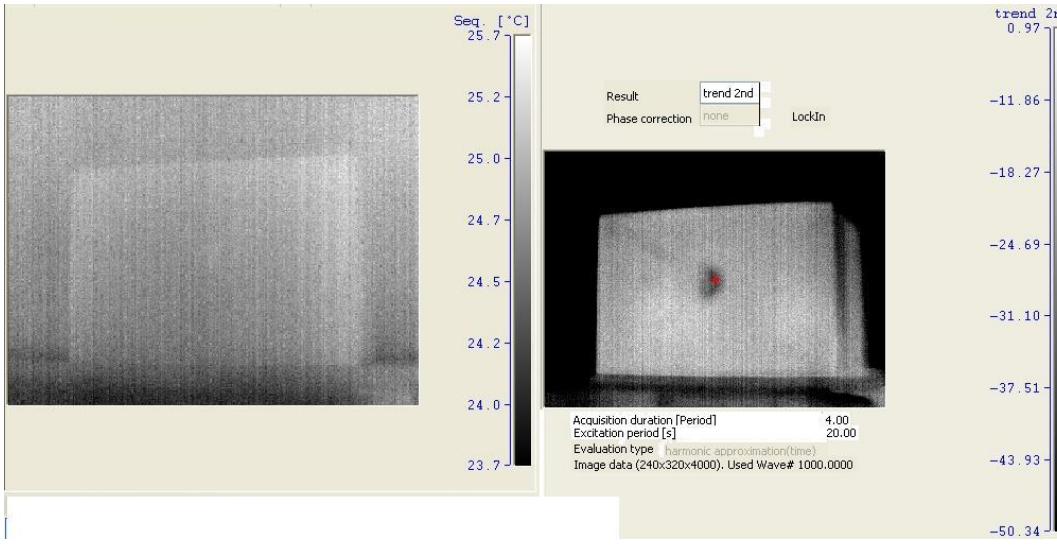


a) Experimental setup b) Thermogram (passive thermography).

Fig. 9 Sandwich GFRP plate with water ingression on the upper side

The most common damages of the composite structures consist in impact damage or battle damage, delaminations and debondings. The composite laminates are usually damage tolerant and it is necessary to detect for example only relatively large delaminations (10-20 mm).

The first example concerns the LT examination of a GFRP sandwich plate subjected to a low velocity impact (LVI) test at 20 J energy level. The figure 10b shows a thermogram obtained with the harmonic approximation (time) analysis method and the second derivative of the temperature field (trend 2nd).

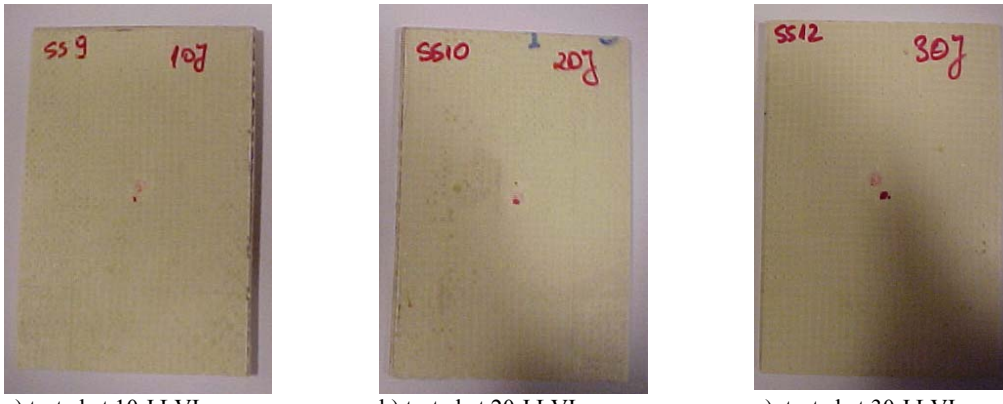


a) Passive image b) LT thermogram

Fig. 10 Thermograms of a GFRP sandwich plate after LVI

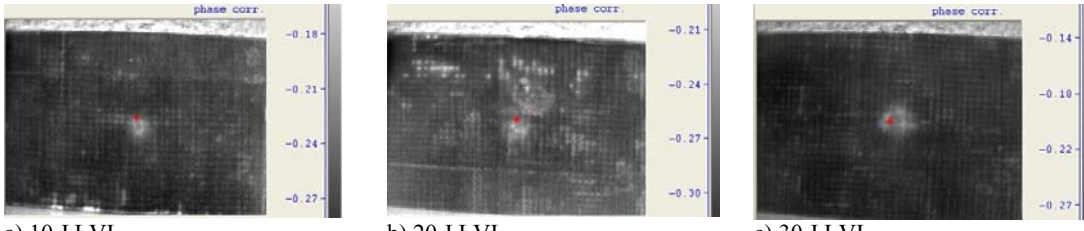
The next examples consist in the LT examination of several GFRP sandwich plates subjected to low velocity impact (LVI) tests at 10J, 20 J and 30J energy levels. The samples are15 cm x 10 cm x 0.8 cm sandwich type plates with faces in composite GFRP (4 layers of a total thickness 2 mm) and core in coremat, 4 mm thick. (fig. 11). The parameters of the examinations were: period 20s (frequency =0.05Hz), total time of the test 100 s (4 periods) with a camera frequency image acquisition of 50 Hz, obtaining 4000 images. The Figure 12

shows the corresponding thermograms (phase based), obtained using harmonic approximation (time) analysis method and the second derivative of the temperature field (trend 2nd).



a) tested at 10 J LVI b) tested at 20 J LVI c) tested at 30 J LVI

Fig. 11 Sandwich plates with GFRP faces + coremat



a) 10 J LVI b) 20 J LVI c) 30 J LVI

Fig. 12 LT thermograms of the impacted sandwich plates

In the case of these impacted samples one can have also visual informations but the IRT allows to see better the extent of delaminations related to the energy of the LVI tests.

5. CONCLUSIONS

Several examples of infrared thermography application to several materials of aeronautical use were presented. The aim of this paper was to focus attention on the aid provided by active Lockin, Pulse or Flash thermography for nondestructive evaluation of aerospace materials. Data herein presented show that IRT supplies useful information, which can be exploited for: detection of defects with evaluation of their size, position and nature; evaluation of the extension of the impact damages; evaluation of the conditions of the core under the skin for sandwich structures; understanding of the behaviour of metallic and fibre/epoxy layers in hybrid composites etc.

However, infrared thermography is not only useful for non-destructive evaluation. In fact, infrared thermography could be enclosed in industrial instrumentation in order to control the entire manufacturing process, from the machine performance (temperature monitoring) to the final product quality (non-destructive evaluation). The objective of this paper was to employ the Infrared thermography in order to detect different defects for typical materials used in aerospace industry. Nowadays IRT is among the emerging NDE methods and is increasingly used in aeronautics together with ultrasonics, eddy currents and other more well established technologies.

CFRP and GFRP samples were investigated by Long Pulse Thermography, using a panel with 4 halogen lamps (actual power 2.6 kW) as heating source, this technique proving to be an appropriate means in the NDE of composite panels. According to the sample thickness and depending on thermal diffusivity of the tested material, one can choose the appropriate heating device and the corresponding test parameters as length of the pulse, acquisition time etc. In materials having high thermal diffusivity, the heat propagation rate is too fast and for example metallic samples have to be examined by Flash Thermography when the injection of heat is performed in a very short time (maximum tens of ms) with a high electric power (a Hensel generator of 6 kJ was used in this study).

Our laboratory is currently involved in the developing and using of such active thermography techniques as Lockin, Pulse and Flash Thermography in order to evaluate the integrity of different type of composite and isotropic materials and structures.

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