PULSED PHOTOTHERMAL NONDESTRUCTIVE TESTING -
APPLICATION TO CARBON EPOXY LAMINATES

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INTRODUCTION

Different methods of NDT of carbon-epoxy laminates have been used up till now, including ultrasonics, X-ray photography and vibrothermography. Thermal methods are now appearing, because they can be contactless and single ended [1-3]. Among these methods, pulsed back emission photothermal radiometry seems attractive because it is a simple method, where elasticity is uncoupled. So the possibility of quantitatively characterizing delaminations is offered, as the model describing the phenomenon is simple. Results recently obtained at the Office National d'Etudes et de Recherches Aérospatiales (ONERA) are presented here to demonstrate that the method is well suited to the detection, in-depth localization and characterization of delaminations in carbon-epoxy composites.

The principle of the method is first presented. For the detection of delaminations, the zero-order temporal moment is simple to calculate. Its theory is described. Then, the method for quantitatively characterizing the defects, based on the apparent effusivity analysis, is presented. We applied these two methods to the detection and the characterization of artificial delaminations in a carbon-epoxy laminate. Experiments are then presented, where an IR camera is used to monitor the temperature variations of the sample. Data reductions, carried out with the recorded frames, are discussed step by step, leading to the results which are compared to the nominal values.

PRINCIPLE OF THE METHOD

In pulsed back emission photothermal radiometry, a sample is heated briefly by an uniform IR or visible source. The front surface temperature increase is monitored by an IR detector. The method of the zero-order temporal moment consists of integrating the temperature increase over the time. For a homogeneous medium heated by a uniform energy density, the temperature-time history being $\Delta T_0(t)$, this moment

$$ M = \int_0^\infty \Delta T_0(t) \, dt $$

tends to infinity. When an internal defect, characterized by its thermal resistance $R$ and its depth location $z$ from the front surface, is present, there is a delay in the heat diffusion and the temperature-time history is modified, becoming $\Delta T_R(t)$. A bump appears in the temperature decrease.
The perturbation $\Delta T_R(t) - \Delta T_0(t)$ in the temperature evolution induces a variation in the moment $M$ and it may be analytically demonstrated \[4\] that this variation is equal to:

$$
\Delta M = \int_0^\infty [\Delta T_R(t) - \Delta T_0(t)] \, dt = Q \cdot R \cdot (1-\frac{z}{L})^2, \quad (1)
$$

where $Q$ is the energy density deposited in the sample and $L$ is its thickness. It is important to note that, if the sample is very thick, $\Delta M$ is equal to $Q \cdot R$ and does not depend on the defect depth. So with the moment, it is very easy to detect defects in the sample, even if they are located very deep. Experimentally, this moment is calculated by adding temperatures, an operation which enhances the signal-to-noise ratio.

Therefore defects characterized by low thermal resistances could be seen with the moment. This method may be very fast for detecting delaminations in such a medium.

Once detected using the moment method, for the characterization of defects, it is simpler to use apparent effusivity. In the case of a semi-infinite homogeneous medium, its effusivity $b$ can be found from the surface temperature evolution $\Delta T(t)$ by:

$$
b = \frac{Q}{\Delta T(t) \sqrt{\pi t}}. \quad (2)
$$

If there is a delamination, the bump in the temperature evolution can be seen as a minimum on the apparent effusivity evolution curve $b(t)$ calculated using (2). An analytical model of the pulsed thermal response of layered materials \[5\] was used to establish a method for in-depth localization of the delamination and measurement of its equivalent thermal resistance $R$ \[6\].

The effusivity evolution $b(t)$ is plotted in normalized variables, relating $b(t)/b_0$ ($b_0$ is the nominal material effusivity) and the Fourier number for the depth $z$ of the delamination $F_{od} = a_0 \cdot t / z^2$, $a_0$ being the diffusivity of the material. With these normalized variables, the curve is completely defined if the Biot number of the delamination $B_{od} = z / k_0 R$ is given; $k_0$ is the conductivity of the medium (see Fig. 1). Each curve can be characterized by one point - for example its minimum, whose coordinates are $(F_{od})_{min}$ and $(b/b_0)_{min}$.

A simple correlation was established, relating $(F_{od})_{min}$ and $(b/b_0)_{min}$:

$$
(b/b_0)_{min} = (F_{od})_{min}^{-0.528} \quad (3)
$$

From this relation, the depth of the delamination is directly derived:

$$
z = \sqrt{a_0 t_{min}} (b / b_0)^{0.95} \quad (4)
$$

where $t_{min}$ is the occurrence time of the minimum of the effusivity evolution. For example, in Fig. 2 are plotted the $b(t)/b_0$ curves for defects with the same thermal resistance and different depths. So, by the use of the $b(t)/b_0$ curve, the depth of the delamination, once detected, can be calculated using expression (4).

A second correlation was established, relating $(F_{od})_{min}$ and $B_{od}$:

$$
(F_{od})_{min} = 1 + 0.62/B_{od} \quad (5)
$$

This way $R$ can be found from the effusivity evolution by:

$$
R = \frac{1.61}{b_0} \cdot \sqrt{t_{min}} \cdot (b/b_0)^{0.95} \cdot \left[ (b/b_0)^{-1.89} - 1 \right] \quad (6)
$$
EXPERIMENTAL CONDITIONS

This NDT method was applied to the characterization of artificial delaminations in a carbon-epoxy laminate. The sample is a 25x30 cm plate of carbon-epoxy, manufactured by Avions Marcel Dassault - Breguet Aviation (AMD-BA). During the process, defects (simulating delaminations) were included in the sample at different depths. These defects consist of pieces of Teflon® sheets of various areas. The sheets, 80μm thick, corresponding to a thermal resistance of 3.10^-4 SI, are equivalent to an air gap 8μm thick. The part of the sample in the field of the IR camera is drawn in Fig. 3.

The experimental setup is shown in Fig. 4. We use the apparatus developed by CEDIP (PTR 8900) [7] to illuminate the sample. It is constituted by a bank of continuous quartz lamps and a rotating shutter intercepting or not the flux delivered by the lamps. This system being not parallel to the sample, the energy density is not uniform on the surface. The emission of the sample surface after the pulse heating is monitored by an IR camera (AGA 782), delivering 25 frames per second. The frames are real-time acquired for several tens of seconds using the system developed by CEDIP, 64 lines and 256 points per line. Data reduction is made with a PC compatible computer in order to detect and characterize the defects in the sample.

Fig. 1. Evolution of the normalized apparent effusivity with the defect Fourier number, for various Biot numbers.

Fig. 2. Evolution of the normalized apparent effusivity for defects with the same thermal resistance (R = 0.02 SI), and various depths.

Fig. 3. Artificial defect arrangement in the carbon-epoxy sample.
Fig. 4. Experimental setup for thermal NDE of samples.

DATA REDUCTION

Fig. 5 shows a typical image, recorded at a time $t = 4.36$ s after the pulse heating, enduring 1 s. This image is constituted from four interlaced frames (256 x 256 pixels). The background non-uniformity is due to inhomogeneous heating and emissivity variations. In this picture, only defects #1-1, 1-2 and 2-1 are visible. It is possible to take into account the non-uniformity in the deposited light and emissivity variations. The temperature in the time just after the pulse heating is not perturbed by the presence of defects. For these times, equation (2) is valid, so the received signal is proportional to $Q$ which depends on the heat flux and the surface emissivity distribution. Therefore, the later images may be normalized by one of the first images (at time $t_0$), leading to normalized images not dependent on $Q$:

$$\frac{\Delta T(t)}{\Delta T(t_0)} = b_0 \cdot \sqrt{t_0} / b(t) \cdot \sqrt{t}$$

Fig. 6 is an example of the result of this process. In this figure, many other defects (#2-2 and 2-5) are visible, this being due to the normalization.

For the defects detection, addition is made over a certain number of recorded frames to obtain the zero-order temporal moment. Fig. 7 shows the result of such an addition, calculated with 61 images. Compared to the previous figure, the contrast of the #1-2, 2-2 and 2-5 defects have been increased and the #1-3 defect is visible.
Fig. 5. Temperature image, acquired at a time $t = 4.36$ s after the beginning of the pulse heating (pulse duration 1 s).

Fig. 6. Normalized temperature image, idem Fig. 5

Normalized apparent effusivity images are deduced from temperature images using relation (7):

$$\frac{b(t)}{b_0} = \frac{\Delta T(t_0).\sqrt{t_0}}{\Delta T.\sqrt{t}}.$$ 

In order to obtain the $$(b/b_0)_{\text{min}}$$ value under the best conditions, the instantaneous value $b(t)$ is replaced by a mean value $\bar{b}(t)$ resulting from the integration of $N$ images, centered on the $i$th image corresponding to the time $t$. This number $N$ is optimized to obtain the defect depth with an accuracy of 5%. Using the analytical model, a criterion was found: $N=0.095 i$. Fig. 8 is the normalized effusivity image, integrated over 2 images around the time $t = 4.36$ s. Due to the good signal to noise ratio,
six defects are visible, including defects #2-2 and 2-5. For the #1-2 and 2-5 defects, this image corresponds to the minimum in effusivity and allows us to measure their depths and their thermal resistances, using equations (4) and (6).

The depths of the defects #1-2 and 2-5 are respectively measured as 1.0 and 1.1 mm. The nominal value is, for these two defects, 1.125 mm. The difference between the measured and the nominal value is due to the signal to noise ratio, giving errors on both b(t) and bo. The resistances for the #1-2 and 2-5 defects are respectively measured as 2.1 and 0.8 10^-3 SI. Here the nominal value 3 10^-3 SI is obtained by calculation from the thickness of the teflon sheet, i.e. 80 μm. In fact, a cross section
machined in a defect area revealed the presence of 20 μm air gaps between the teflon and the material. In this condition, a nominal value of 1.2 $10^{-3}$ SI was estimated for the total thermal resistance equivalent to the defect. It is possible that this value varies from one defect to another. Therefore, it may be supposed that the measured values are good estimations of the actual ones.

CONCLUSION

The possibility of detection, localization and characterization of delamination in a carbon-epoxy laminate by use of a pulsed photothermal method was clearly demonstrated. The use of the moment here presented leads to enhanced contrast images facilitating the detection of defects. It allows us to detect defects 2 mm in depth from the viewing surface for carbon-epoxy composites. For a quantitative characterization of the defects, apparent effusivity is well suited and furnishes two thermal parameters of the delamination: the depth and the thermal resistance. These data reductions seem very promising for a quantitative thermal NDE.

ACKNOWLEDGEMENT

This work was supported by DRET, Direction des Recherches Etudes et Techniques of the French Ministry of Defense.

REFERENCES