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Thermographic Investigation of Heat Source in Transversely Isotropic Composites

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Abstract. This paper deals with the estimation of heat sources from infrared thermographic measures on anisotropic CFRP (Carbon-Fibre Reinforced Composites). Such procedure combines the data processing of the thermal signal, especially as spatial and temporal derivation quantities involved in the heat equation are notably affected by the measurement noise, and the determination of thermo-physical properties of the material, especially to account for the anisotropic conductivity behavior of the material. A comparative analysis of different filtering techniques is done to define a filtering method able to decrease the noise while keeping the useful features of the signal. Then, we use a homogenization scheme based on single-inhomogeneity solutions of Eshelby to derive the transversely isotropic thermal conductivity tensor.

INTRODUCTION

Non destructive techniques really constitute suitable and relevant tools for the study of degradation mechanisms of materials. Without any influence of the measurement operation itself, they allow real time recording under load, spatial investigation and high sensitivity observations. Among them, Infrared Thermography (IRT) provides 2D measurements of surface thermal fields of structures and leads to considerable advances in Non Destructive investigation for structural health analysis and for the monitoring of deformation and damage mechanisms [1,2]. This paper focuses on the latter application to study the mechanical behavior of carbon-epoxy laminated composites under quasi-static tension tests. Previous studies have already demonstrated the interest of acquiring thermal fields to observe and characterize damage processes [3,4]. Yet, these thermal data remain influenced by environmental conditions. Accordingly, it is much more relevant to derive from those measurements related heat sources to obtain intrinsic indicators of involved mechanisms [1]. If such approach is quite common for isotropic (or considered as such) materials [5,6], the present study aims at presenting a complete methodology (see [7]) able to estimate heat sources from a filtered thermal signal obtained by IRT, while accounting for the anisotropic character of composites and preferential conduction directions.

MATERIAL AND EXPERIMENTAL SET UP

In this study, we consider a composite laminate made of 14 unidirectional plies of prepreg HEXPLY® M10R/39%/UD150/CHS. Each 2 mm thickness ply is composed of TORAYCA® T700S carbon fibers and M10 epoxy resin. Accordingly, the material exhibits a transverse isotropy around the fiber direction (0° , associated to unit axis x_1). Then, samples have been cut along 0° and 90° direction (associated to unit axis x_2) according to Standard NF EN ISO 527-5 for tensile tests on composite materials (Fig. 1a).

Mechanical tests have been carried out using a 100 kN electromechanical machine INSTRON® 5500R, at ambient temperature with loading speed of 2 mm/min for 0° tests and 1 mm/min for 90° tests. Thermal acquisition is done with Infrared camera FLIR® Titanium SC7000 (InSb sensors, focal plane of 320X256 pixels, thermal resolution of around 25 mK, Fig. 1b). We have considered an emissivity of 0.98 for the carbon fiber laminate and an acquisition frequency of 150 Hz; given the distance between the sample and the camera, the spatial resolution is smaller than 0.7 mm. Calibration of the system is automatic and data recording is operated with ALTAIR® software. Note finally that analysis is performed on relative temperature field $\Delta T(t) = T(t) - T(t_0)$ (with T the temperature field at time t , and t_0 the initial state at the beginning of the test) to limit as much as possible the disturbances induced by the surrounding.

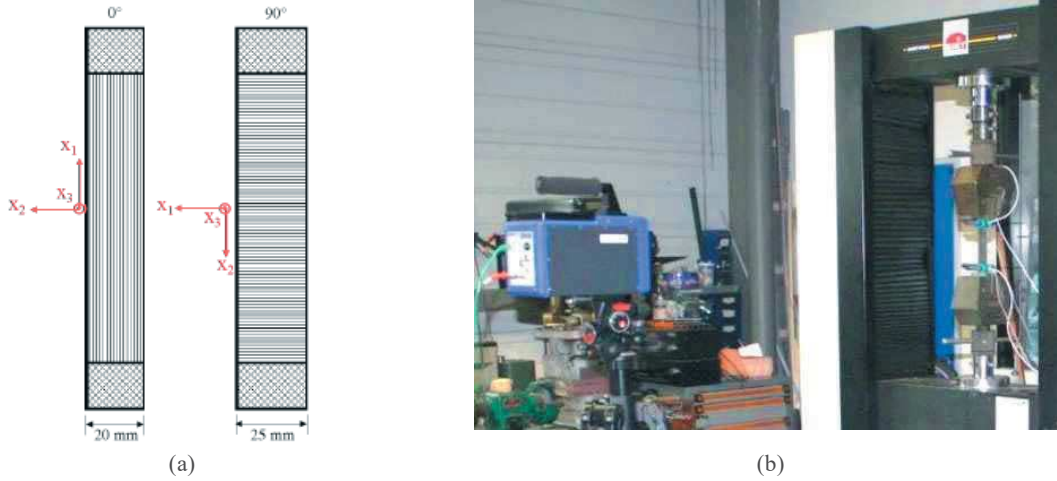


FIGURE 1. Tensile tests on composite laminates: (a) Material orientation, (b) Experimental set-up

HEAT DIFFUSION EQUATION

Thermodynamics of irreversible processes offers an adequate background to interpret time and space dependent temperature data [8]. In the present case, we assume quasi-static processes and small perturbations. Combination of the first (energy conservation) and second (admissible evolutions) principles of thermodynamics with the heat conduction law of Fourier ($q = -\mathbf{k} \cdot \text{grad}T$, with q the heat flux and \mathbf{k} the conductivity tensor) leads to the well-known local equation of heat diffusion:

$$\rho C \dot{T} + \text{div}(-\mathbf{k} \cdot \text{grad}T) = r_{\text{ext}} + s_t \quad (1)$$

where ρ denotes the material density, C its specific heat, \dot{T} the temperature time derivative, r_{ext} the external heat supply and s_t the overall heat source. In view of weak thermal variations induced by the mechanical load, coupling sources between the temperature and irreversible processes, are neglected, so $s_t = s_e + d_1$ with s_e the thermoelasting coupling (that can be deduced from the elastic stiffness, expansion coefficient and load intensity [7]) and d_1 the mechanical intrinsic dissipation which is under investigation here.

Moreover, the conduction problem expressed through Eq. (1) is simplified according to following assumptions: Physical and thermal properties of the material are constant during the test,

- External heat source do not depend on time t ; if the sample does not produce any s_t source in the initial state (at time t_0), then the initial temperature field is in equilibrium and $div(-\mathbf{k} \cdot gradT(t_0)) = r_{ext}$,
- Since composites are thin laminates, the general problem can be considered as a 2D one, by assimilating the surface temperature to the mean temperature in the thickness.

Simplified local heat diffusion can thus be formulated in this way:

$$\rho C \left(\dot{\theta} + \frac{\theta}{\tau} \right) + div(-\mathbf{k} \cdot grad\theta) = s_t = s_e + d_1 \quad (2)$$

where $\theta(t) \cong \Delta T(t)$ denotes the mean value (in the thickness) of the relative temperature field.

DATA PROCESSING

As shown by Eq. (2), the determination of heat sources requires time and spatial derivation of the thermal signal that is discrete and noisy. It is thus necessary to apply in a first step some filtering operation in order to get a proper signal without too much noise and including useful information of the original measurements. Following the approach of [9,10], several filtering methods have been considered and applied to the thermal acquisitions and their derivatives [7,11]. Using Matlab® software, temporal efficiency has been studied with by comparing pixels subjected either to strong damage or to environmental noise (see Fig. 2). The standard deviations of initial and filtered signals are compared during a time interval for the noisy area (Fig. 3a), while the ability of the filter to keep the useful information is studied through the thermal peak amplitude for the strong damage area (Fig. 3b). Note that similar study has been performed regarding spatial efficiency.

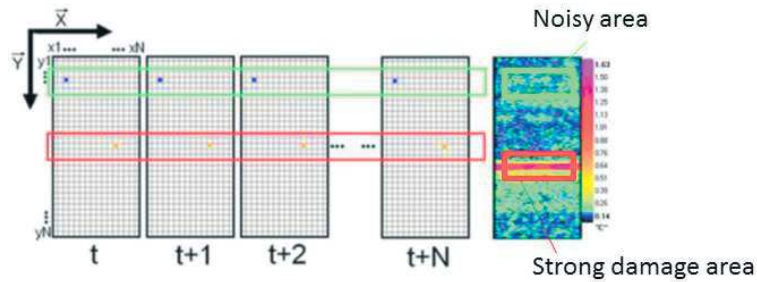


FIGURE 2. Investigated areas for the temporal efficiency analysis (90° laminate)

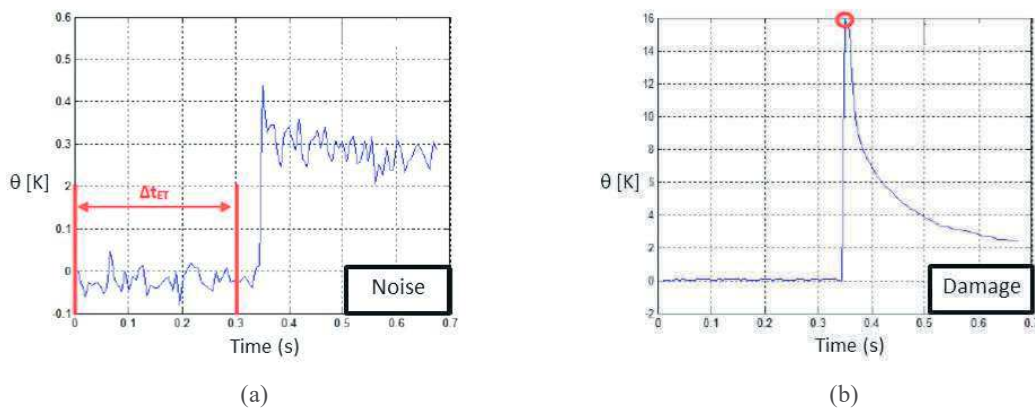


FIGURE 3. Data analysis regarding temporal efficiency: (a) noise attenuation, (b) useful signal attenuation

As an example, we propose in Tab. 1 a quantitative analysis of filtering methods on the temporal derivative $\dot{\theta}$. Using comparative results on all quantities involved in Eq. (2) (see details in [7,11]), it clearly appears that the 3X3 spatial median provides the best filtering method to reduce the noise while keeping essential features of the original thermal response, it will thus be applied in what follows to thermal data θ in order to estimate heat sources.

TABLE 1. Comparison of the efficiency of filtering process regarding temporal derivative $\dot{\theta}$: relative variation of original and filtered signals standard deviations for the analysis of pure noise attenuation and relative amplitude at the thermal peak for the analysis of useful signal attenuation.

Filtering method	Pure noise attenuation	Useful signal attenuation
3X3 spatial median	61%	3%
Spatial FIR Hamming window	28%	2%
3X3 spatial moving average	64%	16%
2X2 spatial moving average	47%	21%
Temporal FIR Hamming window	54%	52%
Temporal FIR Equiripple	62%	59%
Temporal 2 pixels moving average	49%	51%
Temporal 4 pixels moving average	73%	76%
Temporal polynomial smoothing	80%	92%
Temporal IIR Butterworth	63%	58%

MICROMECHANICAL MODELLING

The last stage of the study requires to determine the anisotropic conductivity tensor \mathbf{k} . In view of the lack of experimental data, we have chosen to derive its expression from a micromechanical modelling. According to some assumptions regarding the geometry of the material microstructure and constituents behavior, such approach allows to establish the effective properties of heterogeneous materials [12,13].

In the present case, the Representative Volume Element is the laminate itself that exhibits a matrix-inclusion morphology: fibers are modelled as an infinite cylindrical inclusion of axis x_1 inside the epoxy matrix. It is assumed that both constituents follow the heat conduction law of Fourier, with an isotropic behavior for the matrix and a transversely isotropic (around axis x_1) one for the fiber phase, namely:

$$\mathbf{k}(z) = \begin{cases} \mathbf{k}_m = k_m \mathbf{I} & , \forall z \in V_m \\ \mathbf{k}_f = k_f^L x_1 \otimes x_1 + k_f^T (\mathbf{I} - x_1 \otimes x_1) & , \forall z \in V_f \end{cases} \quad (3)$$

with k_m the matrix conductivity, (k_f^L, k_f^T) the longitudinal conductivity of fibers, \mathbf{I} the identity second-order tensor, (V_m, V_f) the matrix and fiber volumes respectively. Using works on the single-inhomogeneity problem, firstly studied by Eshelby for elasticity problems and then extended to thermoelasticity [14], and the Mori-Tanaka scheme [15], one obtains the following effective conductivity of the composite laminate:

$$\mathbf{k}_{hom} = k_{hom}^L x_1 \otimes x_1 + k_{hom}^T (\mathbf{I} - x_1 \otimes x_1) \quad (4)$$

with the effective longitudinal $k_{hom}^L(k_m, k_f^L, f_f)$ and transversal $k_{hom}^T(k_m, k_f^L, k_f^T, f_f)$ conductivity (f_f the fiber volume fraction) [7]. Given the material properties, such expression allows to account for the material symmetry, namely transverse isotropy, of the laminate for the heat source determination, and thus to introduce the interaction effects between orientational effects of the load and conduction respectively.

PERSPECTIVES

Figure 4 summarizes the approach considered in this study, including the filtering step and source determination based on homogenization theory. Such heat source analysis is clearly original regarding the consideration of the anisotropic conduction inside materials.

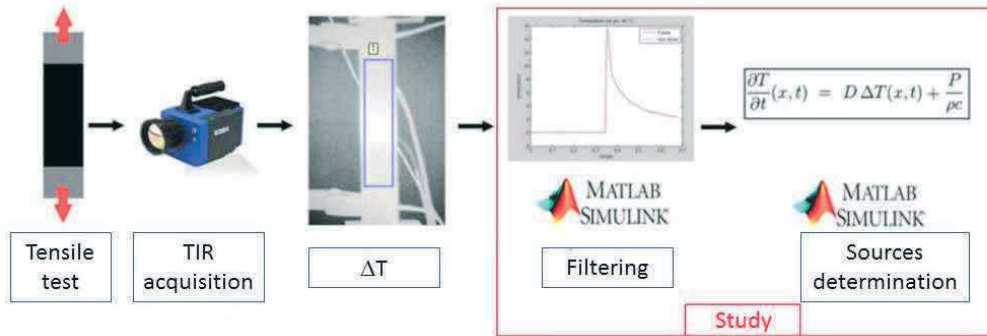


FIGURE 4. Main stages of the method.

At a first point, such methodology allows to highlight degradation process directly on sources quantities and not on temperature fields that remain influenced by environmental conditions. As an example, both temperature fields and related mechanical source fields d_1 are represented on Fig. 5 at two different times during the tensile test on 90° laminate composite. Another interest is the ability to provide a more representative estimation of the conduction than the isotropic assumption usually adopted. Detailed influence of such aspect has been demonstrated in [7]. Finally, it should be noted that this work provides new opportunities to investigate damage process in anisotropic materials, through the determination of thermodynamical quantities that can be directly related to modeling constitutive laws.

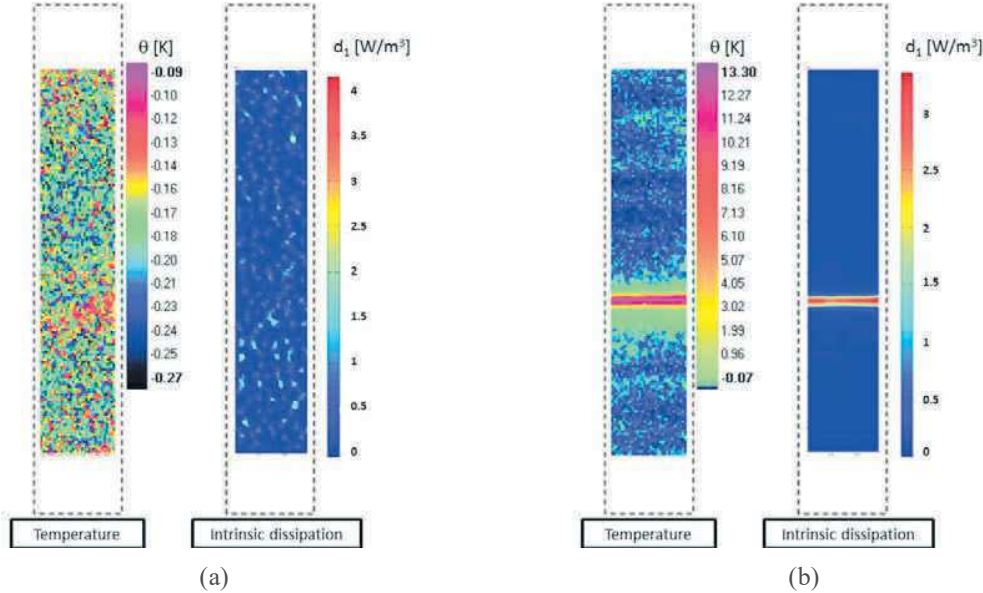


FIGURE 5. Temperature fields and related mechanical source fields d_1 during the tensile test on 90° laminate composite: (a) before failure time, (b) at failure time.

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