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Modeling and characterizing impact damage in carbon fiber composites by thermal/infrared non-destructive testing

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ABSTRACT

Thermal/infrared non-destructive testing (T/I NDT) is a particular application of IR thermography. T/I NDT is typically classified for passive and active, as well as for steady-state (stationary) and transient (non-stationary, or dynamic). Active T/I NDT can be classified by: (1) the type of thermal stimulation, (2) the arrangement of a sample and a thermal stimulation source, and (3) the size and shape of stimulated area.

T/I NDT has proven to be a convenient technique for the detection of impact damage in composite materials due to the following: (1) graphite-based composites are similar to a blackbody by absorption/radiation properties in the infrared (IR) wavelength band, (2) their thermal conductivity is lower than that of metals but higher than of many non-metals thus ensuring reasonable temperature signals at convenient observation times, (3) impact damage leads to thin but laterally-extended air-filled defects which produce considerable thermal resistance to the in-depth heat flux, and (4) T/I NDT is a fast, remote and illustrative technique which, unlike ultrasonic inspection, does not require immersing a sample into water.

This paper describes some approaches to thermal detection and characterization of impact damage in carbon fiber reinforced plastic (CFRP) of whose inspection is an important issue in several industrial areas, first of all, in aero space where subsurface defects might lead to catastrophic consequences.

Realistic solutions of T/I NDT theoretical problems can be obtained by using 3D numerical models of heat conduction. Direct solutions allow better understanding of heat propagation in defect areas while inverse solutions ensure the evaluation of defect parameters, such as defect depth, size and thickness. Several characterization algorithms are available, with a one-sided T/I NDT procedure being better suited for the characterization of defect depth, while defect thickness is best evaluated in a two-sided procedure. In the case of CFRP composites, the defect characterization approaches are well developed, including the technique of dynamic thermal tomography, which enables a considerable reduction of surface clutter and allows the imaging of separate layers of a composite test sample.

1. Introduction

Thermal/infrared non-destructive testing (T/I NDT) is a particular application of IR thermography. Contemporary analysis of material thermal properties goes back to the work of Vernotte (1935), which was devoted to the determination of human skin properties [1]. One of the first implementations of active T/I NDT was the inspection of Polaris rocket motor cases by Beller [2] and nuclear reactor fuel elements by Green [3]. In the 1960s, T/I NDT attracted the attention of aerospace researchers during the “space race”. However, until the end of the 1970s, applications of T/I NDT were mostly qualitative. Quantitative T/I NDT was achieved after the incorporation of elements of heat conduction theory, which was summarized in well-known books by Carslaw and Jaeger [4] and Luikov [5]. A “thermo physical” approach to T/I NDT was developed by Balageas, Vavilov and Taylor, MacLaughlin and Mirchandani, Popov and Karpelson, D. Maillet, S. Andre, J.-C. Batsale et al., A. Rosencwaig and A. Gersho and some other authors who introduced one- (1D), two- (2D) and three-dimensional (3D) models of defects in the 1980s [6–10]. The state of the art of T/I NDT was recently summarized by Maldague [11]. Also, some novel techniques that take advantage of ultrasonic [12] and eddy current [13] stimulation appeared recently.

T/I NDT is typically classified for passive and active, as well as for steady-state (stationary) and transient (non-stationary, or dynamic). Active T/I NDT can be classified by: (1) the type of thermal stimulation, (2) the arrangement of a sample and a thermal stimulation source, and (3) the size and shape of stimulated area.

This paper describes some approaches to thermal detection and characterization of impact damage in carbon fiber reinforced plastic (CFRP) of whose inspection is an important issue in several

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industrial areas, first of all, in aero space where subsurface defects might lead to catastrophic consequences, merely to remind the Columbia disaster in 2003.

2. Statement of the problem

In CFRP, impact damage typically consists of cracks or delaminations, which propagate from the impact site and are oriented along the varying direction of the graphite fibers. It is important that the front (F) surface may exhibit only a faint indication of damage, if any, while delaminations may occur deep in the composite and are often close to the rear (R) surface. A very detailed representation of impact damage can be obtained by an ultrasonic C-scan nondestructive testing technique [14].

T/I NDT has proven to be a convenient technique for the detection of impact damage due to the following: (1) graphite-based composites are similar to a blackbody by absorption/radiation properties in the infrared (IR) wavelength band, (2) their thermal conductivity is lower than that of metals but higher than of many non-metals thus ensuring reasonable temperature signals at convenient observation times, (3) impact damage leads to thin but laterally-extended air-filled defects which produce considerable thermal resistance to the in-depth heat flux, and (4) T/I NDT is a fast, remote and illustrative technique which, unlike ultrasonic inspection, does not require immersing a sample into water.

A classical T/I NDT scheme presumes that a test sample is thermally stimulated on the front surface while temperature monitoring takes place either on the same front surface (one-sided procedure) or on the rear surface (two-sided procedure). The thermal stimulation can be pulsed or periodical, thus resulting in pulsed or thermal wave procedure.

In Section 4, we will consider some basic features of pulsed T/I NDT in application to CFRP. A three-dimensional (3D) Cartesian model of T/I NDT is presented in Fig. 1. A CFRP sample contains 4 air-filled defects with l being the defect depth, d – defect thickness and H – defect lateral size. The sample is heated with a heat flux of the power density Q and pulse duration τ_h. The mathematical statement of the related inspection problem has been thoroughly analyzed by many authors [6–9,15]. Here we report only principal boundary conditions:

$$\frac{\partial T_i(x,y,z,\tau)}{\partial \tau} = \alpha_i^x \frac{\partial^2 T_i(x,y,z,\tau)}{\partial x^2} + \alpha_i^y \frac{\partial^2 T_i(x,y,z,\tau)}{\partial y^2} + \alpha_i^z \frac{\partial^2 T_i(x,y,z,\tau)}{\partial z^2}; \quad (1)$$

$$T_i(\tau = 0) = T_{in}; \quad (2)$$

$$-K^z \frac{\partial T_i(x,y,z=0,\tau)}{\partial z} = Q(x,y,\tau) - h_F[T_i(x,y,z=0) - T_a]; \quad (3)$$

$$-K^z \frac{\partial T_i(x,y,z=L,\tau)}{\partial z} = h_R[T_i(x,y,z=L) - T_a]; \quad (4)$$

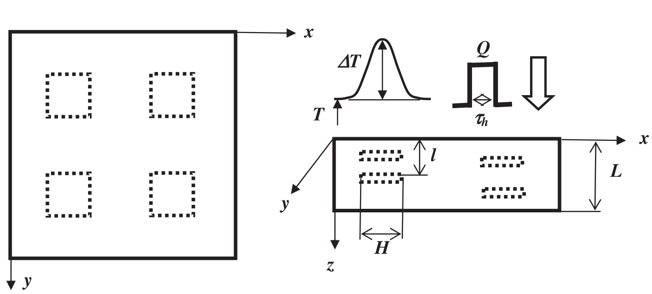

Fig. 1. Active T/I NDT scheme.

$$T_i(x,y,z,\tau) = T_{i\pm1}(x,y,z,\tau) \text{ and } K_i^{q_j} \frac{\partial T_i(x,y,z,\tau)}{\partial q_j} = K_{i\pm1}^{q_j} \frac{\partial T_{i\pm1}(x,y,z,\tau)}{\partial q_j} \quad (5)$$

on the boundaries between the host material and defects.

The physical meaning of Eqs. (1)–(5) is trivial. Here T_i is the temperature in the ith region (a host material and/or defects), T_{in} is the sample initial temperature, $\alpha_i^{q_i}, K_i^{q_i}$ are the thermal diffusivity and the thermal conductivity in the ith region by the coordinate q_j that is one of the Cartesian coordinates x, y, z, τ is the time, $Q(x,y,\tau)$ is the heat flux power density that varies in both time and space, h_F, h_R are the heat exchange coefficients on the front and rear surface respectively, T_a is the ambient temperature (typically, $T_a = T_{in}$), and L is the sample thickness.

3. Detection parameters and conditions

Eqs. (1)–(5) define the so-called direct heat conduction problem of whose solution represents the sample temperature evolving in time. Each defect produces the differential temperature signal $\Delta T(\tau)$ which is a function of heating parameters (Q,τ_h), sample thermal properties (K,α) and defect parameters (l,d,H), see Fig. 1. Note that, due to the linearity of the problem, ΔT is proportional to Q. Another detection parameter is the running contrast $C(\tau) = \Delta T(\tau)/T(\tau)$, where $T(\tau)$ is the sample excess temperature also proportional to Q, therefore, $C(\tau)$ is independent of Q.

A defect can be reliably detected if detection parameters meet the following conditions [16]: (1) $\Delta T > \Delta T_{res}$, where ΔT_{res} is the temperature resolution of the IR camera, (2) $C > C_n$, where C_n is the noise level characteristic for a material under test, (3) $T_m < T_{destr}$, where T_m is the sample maximum temperature linearly proportional to Q, and T_{destr} is the material destruction threshold, and (4) $\Delta\tau = \tau_m/(5 \div 10)$, where $\Delta\tau$ is the IR image acquisition interval, and τ_m is the optimum observation time for ΔT or C. Typically, the most rigid condition of defect condition is $C > C_n$ because of a relatively high level of noise accompanying T/I NDT procedures [15].

4. Basic T/I NDT features

In Section 7, we will present inspection results for the detection of impact damage in an 11.6 mm-thick CFRP sample. Short-pulse Xenon flash tube heating cannot provide sufficient energy to create the required temperature signals to successfully and reliably inspect such a thick composite. Therefore, optical stimulation was provided by a set of halogen lamps whose power density was approximately 18,000 W/m^2. A heat pulse duration of 10 s was able to produce detectable temperature signals. To compare

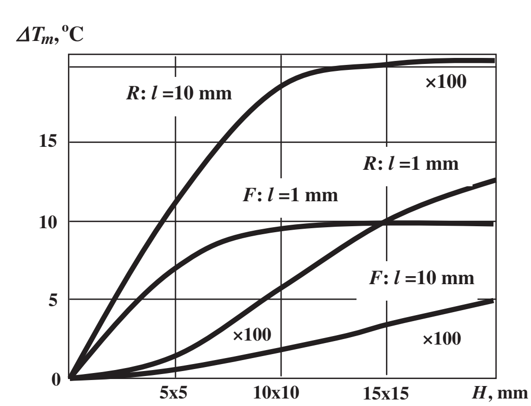

Fig. 2. Differential temperature signal vs. defect size in the inspection of a 11.6 mm-thick CFRP sample (see the legend in Appendix, d = 0.1 mm).