

Evaluation of equivalent defect heat generation in carbon epoxy composite under powerful ultrasonic stimulation by using infrared thermography

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Abstract

Low velocity impact is a frequently observed event during the operation of an aircraft composite structure. This type of damage is aptly called as “blind-side impact damage” as it is barely visible as a dent on the impacted surface, but may produce extended delaminations closer to the rear surface. One-sided thermal nondestructive testing is considered as a promising technique for detecting impact damage but because of diffusive nature of optical thermal signals there is drop in detectability of deeper subsurface defects. Ultrasonic Infrared thermography is a potentially attractive nondestructive evaluation technique used to detect the defects through observation of vibration-induced heat generation. Evaluation of the energy released by such defects is a challenging task. In this study, the thin delaminations caused by impact damage in composites and which are subjected to ultrasonic excitation are considered as local heat sources. The actual impact damage in a carbon epoxy composite which was detected by applying a magnetostrictive ultrasonic device is then modeled as a pyramid-like defect with a set of delaminations acting as an air-filled heat sources. The temperature rise expected on the surface of the specimen was achieved by varying energy contribution from each delamination through trial and error. Finally, by comparing the experimental temperature elevations in defective area with the results of temperature simulations, we estimated the energy generated by each defect and defect power of impact damage as a whole. The results show good correlation between simulations and measurements, thus validating the simulation approach.

Keywords: composites, impact damage, ultrasonic infrared thermography, heat generation

1. Introduction

Current research on ultrasonic infrared (IR) thermography (also called “sonic IR thermography” and “thermosonics”) is being conducted in two main directions: 1) powerful stimulation by using piezoelectric [1–4] and magnetostrictive [5] units, 2) low-power stimulation based on the resonant interaction between ultrasonic waves and defects due to local defect resonance [6]. Although there is lack of complete understanding of the physics governing the heat generation process, it is generally accepted that external ultrasonic stimulation of structural defects causes friction at the defect edges. The generated heat diffuses away from these defects and the corresponding temperature distributions are monitored by using an infrared (IR) camera. Analysis of equivalent heat power produced by a particular defect is of primary interest because, in combination with temperature resolution of a used IR imager, it defines threshold parameters of detected defects. For example, the so-called “kissing” defects may provide frictional heating along the whole defect edge while large defects become thermographically visible only at defect tips where friction predominantly occurs. The defect energy can be accurately evaluated by using both analytical and numerical thermomechanical models that is a challenging task. Thin delaminations which are caused by impact damage in composites subjected to ultrasonic excitation can be considered as local heat sources. Such heat sources operate during



ultrasonic stimulation time and their apparent power depends on the material properties and a mechanism of heat release. This study proposes a further step in this direction to quantitatively evaluate the “defect power” under ultrasonic stimulation.

2. Experimental results

The experimental data was obtained on a 100×150×4 mm carbon epoxy sample which contained a 16 J impact damage defect. The damage was barely seen on the impacted (front) surface as a dent of the size of about 4×4 mm (Figure 1(a)), while on the rear surface the damage was consisted of two extended areas producing the known “butterfly-like” pattern, and its size was about 48×16 mm (Figure 1(b)). Thus we can interpret that the damage has grown in conical fashion through the thickness like a typical low velocity impact damage in composite materials. Note that the piezoelectric sensor shown in Figure 1(a) was not used for the measurements.

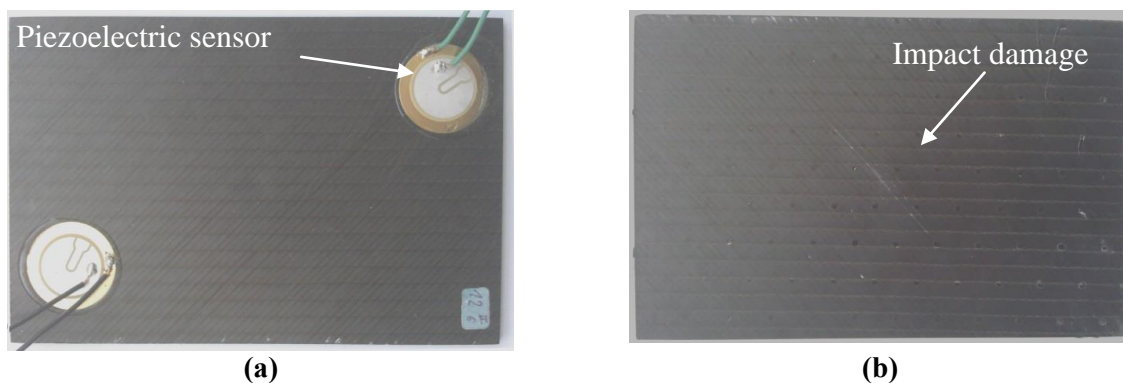


Figure 1. Carbon epoxy composite sample with 16 J impact damage:
(a) front and (b) rear surface.

The sample was ultrasonically stimulated by means of a magnetostrictive device described in [5] (electrical power up to 2 kW, frequency 22 kHz, stimulation time 5-10 s). Test results were recorded on both the sample surfaces as a sequence of IR thermograms by using a NEC TH-9100 IR camera. As can be seen from Figure 2, the maximum temperature rise, due to the application of ultrasonic stimulation for 10 seconds, was 1.04 °C at the defect location on the front surface and 1.65 °C on the rear surface. It is worth noting that on the rear surface the defect pattern revealed two sections (Figure 2(b) & (c)) thus pressing the need to model it with two independent ‘heat source’ delaminations located near the rear surface.

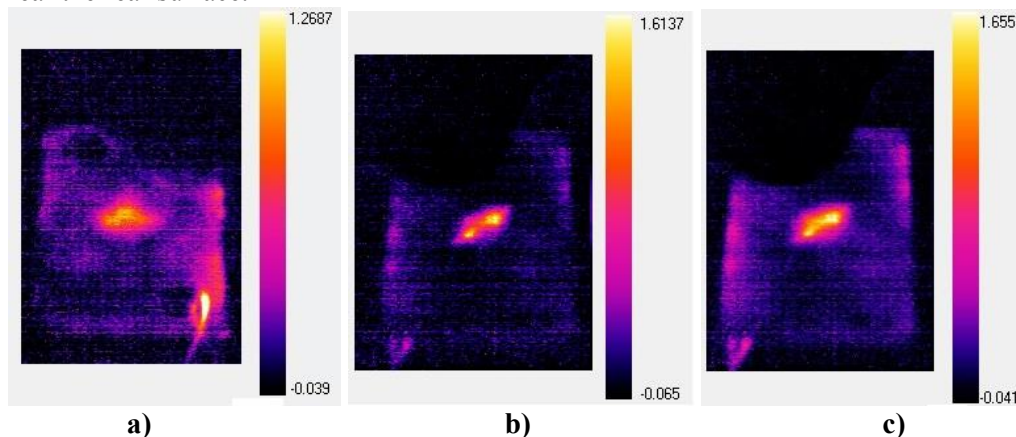


Figure 2. IR thermograms of carbon epoxy composite during ultrasonic stimulation : (a) front surface after 10 seconds of stimulation (b) back surface after 5 seconds of stimulation (c) back surface after 10 seconds of stimulation.

3. 3-D modeling and simulation

As discussed in section 2, we have assumed that impact damage can be modeled as a cone, or a pyramid in the Cartesian coordinates, containing multiple delaminations. A particular cross-section of this pyramid (Fig.3) represents the delaminations which generate thermal energy under ultrasonic stimulation. This particular impact damage was modeled as a set of 9 parallelepiped-like air-filled heat sources each having thickness of 0.4 mm. The distance between the adjacent layers was 0.2 mm. Two rear-surface defects were modeled as two different sections in accordance with the visible pattern (Figure 3). Model parameters were set closer to the experimental values (sample thickness 4 mm, thermal conductivity 0.8 W/(m°C), heat capacity 760 J/(kg°C) and density 1560 kg/m³).

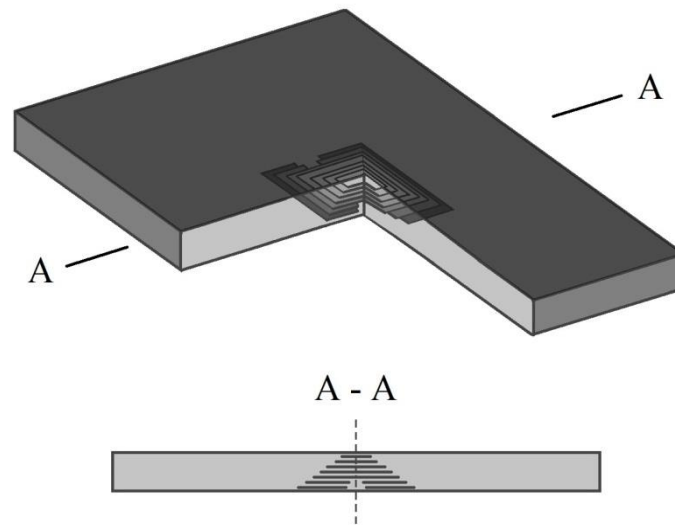


Figure 3. Modeling impact damage as a set of multiple delaminations (Cartesian coordinates, pyramid-like defect shape).

Since pixel-based temperature evolutions were obtained by analyzing experimental image sequences, the next step was the simulation of the surface temperature signal by varying the temperature responses from each delamination so as to match the simulated temperature vs. time graph to the experimental graph and to calculate the “defect power”. The corresponding 3D thermal NDT problem of transient heat conduction was solved by using a home-made ThermoSource program. The mathematical formulation of the problem was as follows:

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

$$i = 1 \div 16 \text{ (seven layers + nine defects)}$$

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

$$K_1^z \cdot \frac{\partial T_1(x, y, z = 0, \tau)}{\partial z} = h_F \cdot [T_1(x, y, z, \tau) - T_{amb}]; \quad (3)$$

$$K_3^z \cdot \frac{\partial T_3(x, y, z=L_z, \tau)}{\partial z} = -h_R \cdot [T_3(x, y, z, \tau) - T_{amb}]; \quad (4)$$

$$\frac{\partial T_i(x, y, z, \tau)}{\partial x} = 0 \text{ for } x=0, y=0 \div L_y; x=L_x, y=0 \div L_y; \quad (5)$$

$$\frac{\partial T_i(x, y, z, \tau)}{\partial y} = 0 \text{ for } y=0, x=0 \div L_x; y=L_y, x=0 \div L_x; \quad (6)$$

$$T_i(x, y, z, \tau) = T_{i\pm 1}(x, y, z, \tau) \quad (7)$$

$$K_i^{q_j} \cdot \frac{\partial T_i(x, y, z, \tau)}{\partial q_j} = K_{i\pm 1}^{q_j} \cdot \frac{\partial T_{i\pm 1}(x, y, z, \tau)}{\partial q_j} \quad (8)$$

Here: T_i is the temperature in the i -th region counted from the initial object temperature ($i = 1 - 7$ corresponds to specimen layers (if a composite consists of 7 plies), $i = 8 - 16$ corresponds to 9 internal heat sources); T_{in} is the specimen initial temperature; $\alpha_i^{q_j}$, $K_i^{q_j}$ are the thermal diffusivity and the thermal conductivity in the i^{th} region by the coordinate q_j ; x, y, z are the Cartesian coordinates; q_j is one of the Cartesian coordinates x, y or z ($j = 1 - 3$); τ is the time; $w(x, y, \tau)$ is the heat power density designated to internal heat sources; h_F, h_R are the heat exchange coefficients on a front and rear surface respectively; T_{amb} is the ambient temperature; L_x, L_y, L_z are the sample dimensions.

Eq. (1) is the 3D parabolic equation of heat conduction; Eq. (2) is the initial condition; Eq. (3) is the boundary condition on a front surface (both heating and cooling); Eq. (4) is the boundary condition on a rear surface (cooling only); Eqs. (5) and (6) are the adiabatic conditions on side surfaces by the coordinates x and y respectively; Eqs. (7) and (8) are the temperature and heat flux continuity conditions on the boundaries between the layers and between the layers and the heat sources respectively.

The power of heat generation in each of the 9 defects was varied by performing repeated calculations to match the experimental temperature evolutions on both the sample surfaces through trial and error. Since the maximum temperature rise is fully determined by the total power of all heat sources, which can be easily determined by comparing maximum experimental and theoretical values, the main difficulty was the fitting of the temperature response curve shape which is affected by the depth location of each heat source. The fitting results are presented in Figure 4.

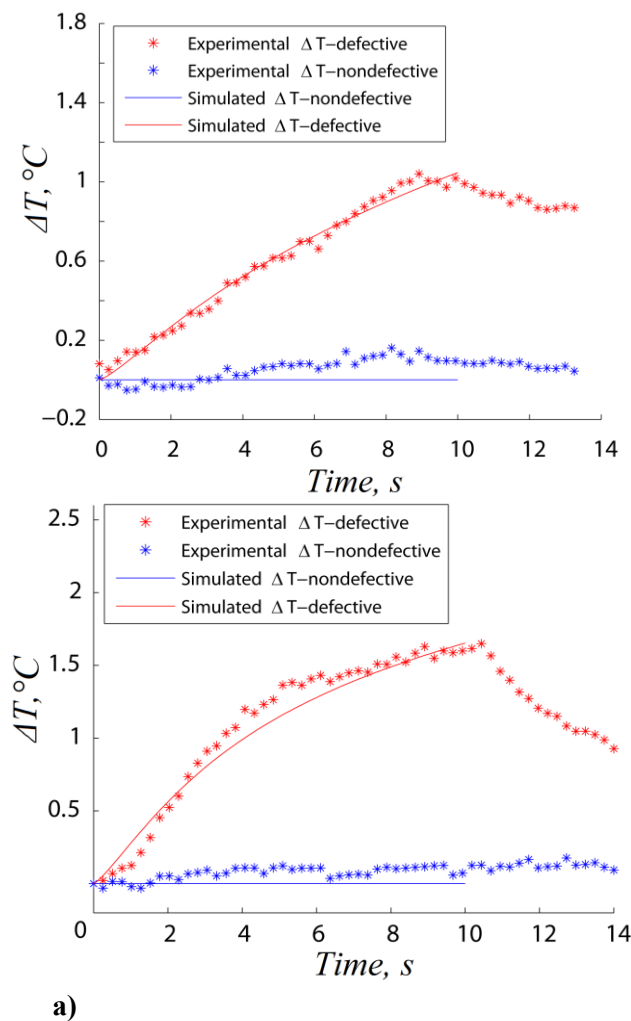


Figure 4. Fitting experimental (a) front and (b) rear surface temperature evolutions by using the model in Figure 3 (heat source operation time 10 s).

Table 1 contains values of particular defect section volumes (V) and their depths (l), as well as estimated heat power (Q), combination of which provides the best fitting of the experimental data (Figure 4). The total “defect power” is 152.9 mW that is in accordance with estimates obtained earlier [7].

Table 1. Fitting parameters in modeling heat generation in impact damage defect (ThermoSource program, ultrasonic stimulation time 10 s)

Defect number	1	2	3	4	5	6	7	8	9
$V, \times 10^{-9} \text{ m}^3$	6.4	24	42	64	120	104.4	111.4	133.5	119.8
$l, \text{ mm}$	0.1	0.6	1.1	1.6	2.1	2.7	2.7	3.3	3.3
$Q, \text{ mW}$	2.75	8.88	12.6	17.28	26.4	20.88	22.28	22.03	19.8

Figure 5 shows temperature responses which would appear if subsurface heat sources are turned on consecutively starting from the inspected sample surface. It is seen that major contribution to the total temperature rise is provided by the first three defect sections which are closer to the inspected surface. The corresponding sample thickness considering these first three defect sections is 1.5 mm.

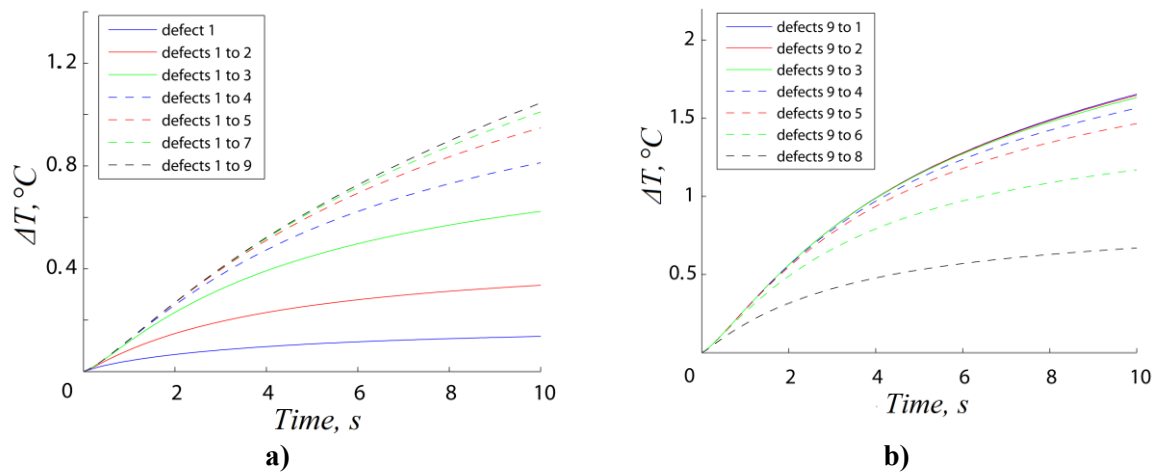


Figure 5. Total temperature response obtained by consecutively turning on subsurface defects for (a) the front and (b) the rear surface (heat source operation time 10 s).

4. Conclusions

In this work, we demonstrated an approach for the evaluation of equivalent thermal power of subsurface defects which operate as heat sources under ultrasonic stimulation. We have restricted our calculations to the case of impact damage of 16 J in a carbon epoxy composite plate. This particular impact damage was modelled as a set of multiple delaminations each acting as a heat source. After the application of ultrasonic stimulation for 10 seconds, experimental measurements showed a maximum temperature rise of 1.04 $^{\circ}\text{C}$ and 1.65 $^{\circ}\text{C}$ at the defect location on the front and rear surface respectively. During the temperature simulations, the power of heat generation in each of the 9 defects was varied by performing repeated calculations, to match the experimental temperature evolutions on both the sample surfaces through trial and error. Thus, the total “defect power” calculated for the impact damage of 16 J was 153 mW that is in accordance with estimates obtained in earlier works (by taking into account the power of ultrasonic stimulation which determines differential temperature signals). It was also found that the major contributions towards the temperature rise were made by defects located within the 1.5 mm-thick material layer adjacent to the monitored surface. The main difficulty was the matching of the temperature response curve shape which was affected by the depth location of each heat source. In all future cases, the simulation approach validated in this paper will be a valuable tool to estimate the defect power and to predict the possible through the thickness positions of the major delaminations in composite materials.

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