NONDESTRUCTIVE TESTING OF MULTI- LAYER COMPOSITES MADE OF CARBON FIBRE BY IR THERMOGRAPHY METHODS

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1 Introduction

Multi-layered composites are frequently used in many military applications and one of them is fabrication of light-weight ballistic covers. An interest in these covers results from threats to which troops participating in stabilisation missions are exposed. Usually these troops are equipped with motor vehicles exposed to small-arms fire and mine explosions. Therefore it is necessary to provide effective protection for these vehicles that will assure an adequate safety level for their crews [1]. Composite materials feature excellent mechanical and strength-related properties, combined with a low specific weight. This combination of features actually occurs only in composites and this is the reason why their application in designs of light ballistic covers, where these features are of paramount importance, has been recently growing rapidly. One of the basic groups of reinforcement materials in composites are carbon fibres discovered back in 19th century [2]. They have many technical applications including light ballistic covers where they usually occur as multi-layer composite materials constituting a structure made of several interconnected or many layers of carbon fibres or in connection with other materials.
Given the fact that light ballistic covers are usually several to 10-20 mm thick and are made of materials with thermo-physical properties definitely different from those of potential defects occurring in these materials, non-destructive tests using thermography methods may be effective in detecting these defects.

In this paper both modeling and experimental results, which illustrate advantages and limitations of IR thermography in inspecting composite materials, will be presented.

2 Modeling thermal NDT for multilayer composites made of carbon fibre structure

In order to determine the potential use of thermal methods for non-destructive testing of samples of multilayer composite the computer simulations were carried out at the deployment of specialized software ThermoCalc-6L™ (developed by V.Vavilov for needs of MIAT). This software is intended for calculating 3 D (three-dimensional) temperature distributions in anisotropic six-layer solids that may contain subsurface defects. A solid body is modeled in Cartesian coordinates. The program is based on solving a heat conduction problem by using an implicit finite-element numerical scheme. Originally, ThermoCalc-6L™ was developed for simulating thermal nondestructive testing (NDT) problems where transient temperature signals over subsurface defects are of a primary interest. These signals evolve in time and diffuse in space. The unique numerical algorithm implemented in ThermoCalc-6L™, unlike most commercial software currently available, enables modeling for very thin defects in rather thick materials without losing computation accuracy. It allows analyzing defects for a specimen being heated uniformly or non-uniformly with a square or cosine pulse that gives a unique possibility to study defect cross-influence and lateral 3 D heat diffusion. The software assumes that both the sample tested and defects have a parallelepiped-shape. The sample is heated or cooled down on a front surface with an external heat pulse. The front surface heat flux is assumed to be uniform or Gaussian. The heat flux center can be located at any point on a front surface. Along with the main heating or cooling stimulation, both front and rear surfaces are cooled down according to the Newton law (within such approach, both convection and radiant heat exchange

mechanisms are combined). Thermal properties of a specimen and defects can be specified separately in all three spatial directions thus modeling a fully anisotropic specimen. The specimen side surfaces are adiabatic. Temperature and heat flux continuity conditions change on the boundaries between the specimen layers and between the host materials and the defects and are taken into account. In ThermoCalc-6L™, the conception of the so-called capacitive defects is realized. This means that, unlike resistive defects involved in some other NDT models, both the thermal diffusivity and conductivity of defects are taken into account. This provides the most correct description of physical phenomena occurring in areas of defects.

A 5-layer structure to be tested consists of 3 layers of carbon fibre joined with epoxy resin glue (2 layers). The layer thicknesses are: 1 mm – carbon fibre, 0.1 mm – resin. Two kinds of defects were simulated: air-filled and aluminium foil. Air-filled and aluminium foil defects can be located within resin layers varying in thickness from 0 to 0.1 mm. The structure is heated on the front (F) surface with a heat pulse (τ_h -heat pulse duration; Q -heat power density). The temperature can be monitored on both the F- and rear (R) surface. The carbon fibre is anisotropic, and the sample is non-adiabatic.

The thermal properties of the materials are assumed as follows:

carbon fibre – conductivity perpendicular to fibers $\lambda_{\perp} = 0.64 W/(m \cdot K)$;

conductivity parallel to fibers $\lambda_{\parallel} = 1.28 W(m \cdot K)$

density $\rho = 1500 kg/m^3$;

heat capacity $c = 846 J/(kg \cdot K)$;

diffusivity perpendicular to fibers $\alpha_{\perp} = 0.418 \cdot 10^{-6} m/s^2$;

diffusivity parallel to fibers $\alpha_{\parallel} = 1.84 \cdot 10^{-6} m/s^2$;

epoxy resin – conductivity $\lambda = 0.21 W/(m \cdot K)$;

density $\rho = 1166 kg/m^3$;

heat capacity $c = 1190 J/(kg \cdot K)$;

diffusivity $\alpha = 0.09 \cdot 10^{-6} m^2/s$;

air (in thin gaps) - conductivity $\lambda = 0.07\ W/(m \cdot K)$; density $\rho = 1.2\ kg/m^3$;

heat capacity $C = 1005\ J/(kg \cdot K)$;

diffusivity $\alpha = 5.8 \cdot 10^{-5}\ m^2/s$;

aluminium foil – conductivity $\lambda = 177 W/(m \cdot K)$;

density $\rho = 2770 kg/m^3$;

heat capacity $c = 875 J/(kg \cdot K)$;

diffusivity $\alpha = 73 \cdot 10^{-6} m^2/s$.

The structure to be analyzed can be naturally simulated by **Model 1** and **Model 2** (Fig. 1).

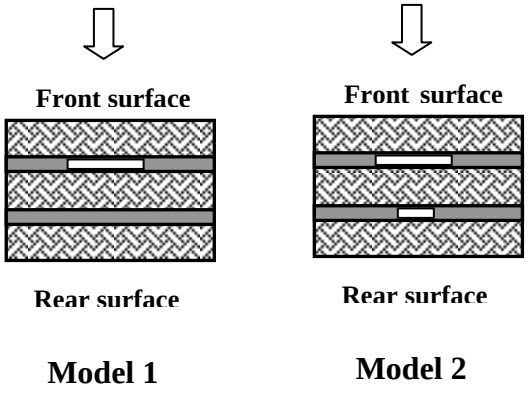


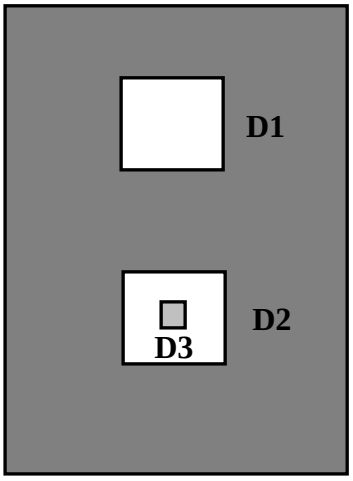
Fig. 1. Thermal NDT model

Within the above-mentioned **Model 1**, defect (air-filled or aluminium) located at the depth 1 mm (defect depth counted from F-surface) have been analyzed. The thickness of the defects was 0.1 mm and the lateral size 20 mm. Two defects (one of air-filled and second of aluminum) located at the depths 1 mm and 2.1 mm are simulated by **Model 2.** These defects are located one under second. The location of the defects within the ThermoCalc-6L program is shown in Fig. 2.

I assume that a defect can be reliably detected by its surface temperature 'footprint' if the corresponding sample excess temperature T and the signal ΔT meet the following conditions:

- a sample maximum excess temperature $T(\tau_h)$ that occurs at the end of heating is lower than the destruction temperature of the sample material T_{destr} (this condition puts a limit onto heat power density and heat pulse duration);
- a ΔT signal must exceed a temperature resolution of a used IR system ΔT_{res};

- a running temperature contrast $C = \Delta T(\tau)/T(\tau)$ must exceed the noise level that adheres to each material and surface condition (for example, it is known that even 'black' coatings might reduce noise only up to 2% in terms of the noise running contrast C_n) .



D1 – size 20x20 mm, depth 1 mm
D2 – size 20x20 mm, depth 1 mm
D3 – size 5x5 mm, depth 2.1 mm

Fig.2. Location of defects in ThermoCalc-6L

Optimum detection parameters for defects 1-6 can be calculated as shown in Table 1.

Defect	ΔT, ˚C	τ_m, s	C, %
Air-filled D1	0.29	3.45	9
Air-filled D2+D3	0.34	3.53	8
Aluminium D1	-0.51	1.67	11
Aluminium D2+D3	-0.58	1.78	15

Tab. 1. Expected detection parameters in the front-surface flash test (τ_h =0.01 s; Q =3·10^5 W/m^2, defect thickness 0.1 mm)

Let me assume that $\Delta\tau = 0.025\ s$ (frame frequency 50 Hz), $\Delta T_{res} = 0.1^oC$ and $C_n = 2\%$. Applying the detection criteria to the data in Table 1 the following can be stated:

- the sample maximum surface temperature will not exceed 100°C;
- all defects meet the condition $\tau_m \geq (5 \div 10)\Delta\tau$;
- the defects produce $\Delta T > 0.1^oC$;
- the defects produce $C > 2\%$.

3. Experimental testing

Pulsed Thermography (PT) [3], which is one of main methods of active thermography, was used to check the effectiveness of defect detection in multi-layer carbon composites.

Pulsed thermography is currently one of the most popular methods used in non-destructive tests of composite materials. Tests of this kind consist in use of a lamp, laser, etc. to generate a thermal exciting pulse (or series of pulses) that lasts from several milliseconds for high thermal conductivity materials (e.g. metals) to several seconds for low conductivity materials. Also a pulse that cools down the surface of the object being tested can be used (e.g. liquid nitrogen, etc.). Pulsed thermography can be used in both reflective and transmission method. A sequence of images (thermograms) is recorded at constant intervals between the images. Having switched the radiation source off the tested object is cooled down to the ambient temperature. In the cooling phase a temperature distribution across the surface of the object is determined and analysed. Depending on thermal properties of the material tested and defects hidden under its surface, areas of higher or lower temperatures will indicate zones where material defects may occur. Often special thermogram processing techniques need to be used to identify the defect areas.

Several algorithms (such as Fourier transformation, normalisation, polynomial adjustment, pulsed phase thermography, principal components analysis, correlation analysis and dynamic thermal tomography) were used for analysis of the results. These algorithms are used in thermography non-destructive testing for separation of signal change areas against the background of interference [4].

Signal to noise ratio (S) [1] was used as a comparison criterion in estimation of the image processing algorithms used. Basing on the signal to noise ratio it can be estimated which algorithm is more effective in identification of areas where defects are located [4].

3.1. Experimental tests

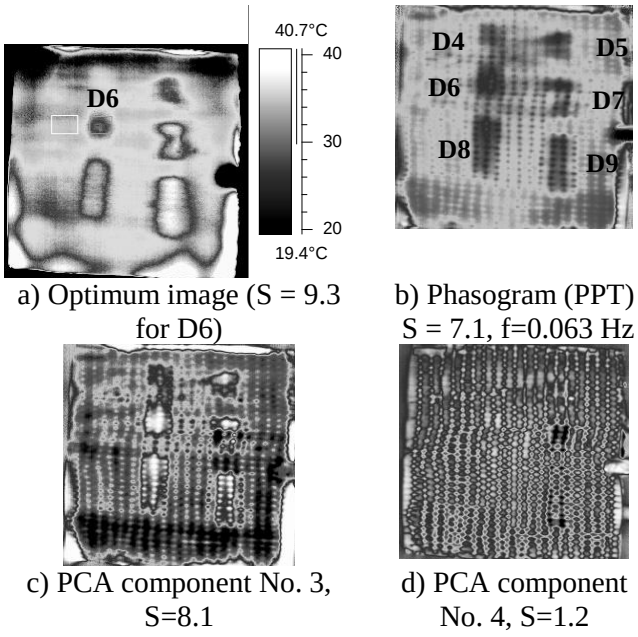
Two samples of a multi-layer carbon-fibre composite were tested in the experimental tests. In order to compare the defect-detection efficiency with use of various image processing algorithms used in thermographic tests, trials of another composite sample of dimensions of 100x100 mm and 5- mm thick, made of 4 layers of carbon-fibre fabric, connected with epoxy resin, were conducted. Six defects (D4 to D9) of dimensions of 5x5 mm, 10x10 mm and 10x20 mm, made of 0.1 mm thick Teflon film and simulating delaminations of the composite, were placed between the fabric layers at different depths (1.2 mm, 2.5 mm and 3.8 mm). The sample was tested by means of pulsed thermography, and the heat source was a flash lamp providing a thermal pulse (Dirac pulse) of 3 kJ output power and 2.7 ms duration. The Agema 900 LW IR camera (detector MCT, 272x136 pixels, 80 mK) was used for recording temperature changes on the sample surface.

Two defects (D10 and D11) of various dimensions of 20x20 mm and 5x5 mm, made of 0.1-mm thick aluminium foil, simulating position of one defect under second (D10 at 1mm depth and D11 at 3.1 mm depth), were introduced into the second sample that was 4.2 mm thick. A flash lamp was used as the source of the optical pulse that provided a thermal pulse (Dirac pulse) of a 6 kJ output power and duration of 1 ms. The SC 7600 IR camera (640x512 pixels, 20 mK) was used for recording the changes of temperature field on the sample surface; the camera was recording sequences of thermograms (1000 images in a sequence) at 100 Hz frequency.

3.2. Test results

Fig. 3 presents selected results obtained from the single-side method that turned out to be more effective in detection of defects in first sample. It is clearly visible that the pulsed-phased thermography method (phasogram Fig.3 b) and principal components analysis (Fig. 3 c) allow for detection of all defects.

Within the testing of the second sample a sequence of 1000 thermograms was recorded at frequency of 100 Hz. The tests were conducted by means of both the pulse single-side pulse method (camera and stimulation source are on the same side of the sample being tested) and double-side one (camera and source are located on opposite sides of the sample). Fig. 4 presents selected results obtained from the single-side method that turned out to be more effective in detection of defects in this sample. It is clearly visible that the pulsed-phased thermography method (PCA component No. 2 Fig.4d) and normalization analysis (Fig. 4 f) allow for detection of D11 and D10) defects respectively.



a) Optimum image (S = 9.3 for D6)

b) Phasogram (PPT) S = 7.1, f=0.063 Hz

c) PCA component No. 3, S=8.1

d) PCA component No. 4, S=1.2

Fig. 3. Results of a carbon-fibre composite test at the pulsed thermography method (single-side method)

4. Conclusions

1) Divergences appeared between obtained results from modeling and the experiments. These divergences are due to an inhomogeneous heating of front surface of the sample and differences between thermal parameters of materials accepted to modeling and real ones for testing sample.
2) The tests of both samples have shown that currently there are technical possibilities of detecting very thin defects in subsurficial layers of carbon-fibre multi-layer composites by means of IR thermography methods.
3) Applied method of results analysis made possible detection for both defects (second sample – results Fig. 4) only in case when the smaller defect (D11) was over a larger one (D10).

4) Future work will be focused on more effective analysis algorithms of data which (for example thermal tomography [5]) could make possible the detection of a smaller defect under a larger one.

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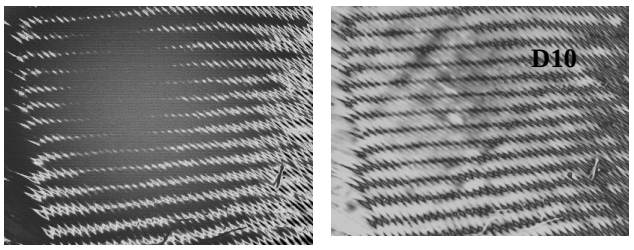
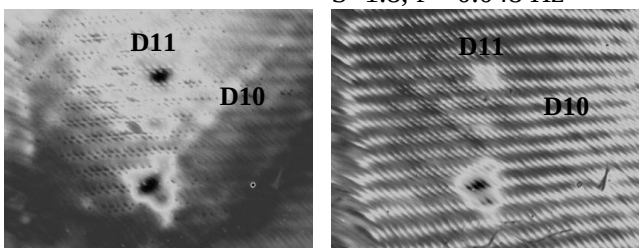
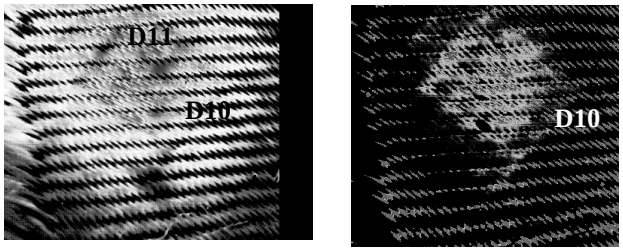


a) Source thermogram b) Fourier phasegram S=1.8, f = 0.048 Hz



c) PCA component No. 1, S = 3.5 d) PCA component No. 2, S = 4.2



e) Correlogram S = 1.9 f) After normalization S = 5.3

Fig.4. Results of a carbon-fibre composite test at the pulsed thermography method (one defect under second defect)

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