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INFLUENCE OF THERMAL SIGNAL CHARACTERISTICS ON DEFECT DETECTION IN GFRP BY ACTIVE OPTICAL THERMOGRAPHY

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Abstract

Advances in technological development, since the 1990s, has been associated with the development of two basic domains of knowledge: information technology and material engineering. The development of material engineering is directly related to composite materials. One group of composite materials are fibre-reinforced composites. Due to their unique properties, they are used in various fields of engineering sectors. Composites reinforced with glass fibre (GFRP) are the second most commonly used composite after carbon fibre reinforced composites (CFRP). GFRP in many cases can replace traditional structural materials, which are usually made from metal. Of course, this material is exposed to damage both in production and operation phases. One method of non-destructive testing that effectively identifies defects in GFRP is active optical thermography. In this method, for thermal stimulation of the tested material, various types of heat sources are used for example: heating lamps, lasers etc. This article analyses the influence of the characteristics of the thermal optical sources on detection of typical defects in GFRP.

Keywords: *non-destructive testing, composite material, IR thermography*

1. Introduction

Fibre-reinforced composites are the most effective composite materials in the sense that they exhibit the best mechanical and strength properties at the lowest specific gravity. This composite combines materials with very different stiffness and strength – on the one hand stiff, brittle and on the other, elastic fibres of the receptive matrix [1]. The first fibre manufacturing technology was developed in the 40s of the last century and was glass fibre. Glass fibres are cheaper than the later-developed carbon and aramid fibres. For this reason, glass fibre reinforced plastic composite (GFRP) is also widely used. This composite has both advantages and disadvantages; advantages include its high tensile strength, resistance to corrosion, electromagnetic indifference, low thermal and electrical conductivity, high fatigue strength, low density, and it is easy to cut. The disadvantages include low modulus of elasticity, low resistance to UV radiation, high coefficient of thermal expansion in the direction transverse to the fibres, and low fire resistance. These composites are widely used primarily in the aerospace, boatbuilding, and construction industries as well as in electronics [2].

Both solid and cored laminates share a common structural feature whereby they need to have a resin to hold both fibres and core material in a fixed orientation. Structural failure of solid laminates shows the damage as the resin either releasing from the fibre or releasing of the layers of cloth (delamination). Structural failure in cored laminates is experienced as delamination as well as failure of the bond between the interfaces of the resin impregnated fibres and the sandwich of core material (disbond) [3].

One of the methods of non-destructive testing used in defect detection in GFRP is infrared thermography. In active infrared thermography, there are many methods of thermal excitation of material in order to detect any defects in it. The most popular of these is optical stimulation by means of various types of heating lamps [4-6]. The heat pulse generated by means of the lamp may have different characteristics and so, numerical calculations were carried out in this article using specialized software, dedicated to this type of research, in order to determine the most effective method of heating.

2. Numerical modelling of pulsed thermography

The Thermo-Calc^{TM}30L program was used to assess the influence of changes in thermal excitations on the possibility of detecting defects in the form of delamination in a multi-layer composite structure made of fiberglass-reinforced plastic. Calculation algorithms used in this software are described in detail in papers [7, 8]. The program assumes that both the sample under test and any subsurface defects have a parallelepiped shape. Heating by means of an external thermal pulse is applied on the side of the front surface of the sample. In addition to stimulated heating, the front, and back surfaces, according to Newton's law, are subject to cooling (this process also involves heat exchange by convection and radiation). For this purpose, appropriate heat transfer coefficients are introduced. Thermal parameters of the sample as well as defects can be determined independently in all three planes of space, thanks to which these elements can be characterized by full anisotropy. The model assumes that the lateral surfaces of the sample are adiabatically insulated and there is continuity while the temperature is maintained between the boundaries layers of the sample and the defects and their environment. For numerical calculations, the applied thermal excitations are shown in Fig. 1.

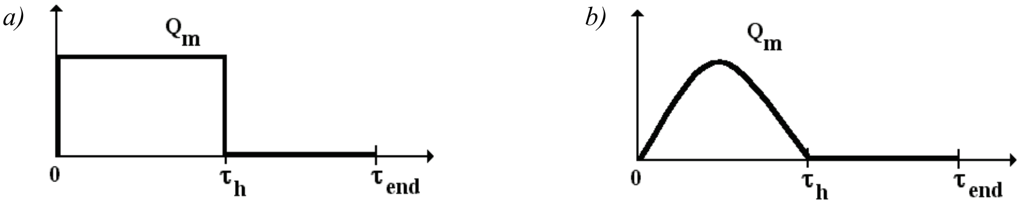


Fig. 1. Type of heating realize in Thermo-Calc^{TM}30L: a) square single pulse heating, b) single cosine-pulse heating

A single square – pulse heating shown in Fig. 1a – in the time interval from 0 to τ_h has a maximum value of Q_m, and in the time interval from τ_h to τ_{end} there is a cooling phase and thermal excitation has a zero value, which describes the dependence [8]:

$$Q(t) = \begin{cases} Q_m & \text{for} \quad t \le \tau_h \,, \\ 0 & \text{for} \quad \tau_h < t \le \tau_{end} \,. \end{cases} \tag{1}$$

A single cosine – pulse (harmonic) heating shown in Fig. 1b – in the time interval from 0 to τ_h can be described by the formula:

$$Q(\tau) = \frac{Q_m}{2} - \frac{Q_m}{2} \cdot \cos\left(\frac{2\pi\tau}{\tau_h}\right). \tag{2}$$

In the time interval from τ_h to τ_{end} there is a cooling phase and thermal excitation has a zero value.

To verify the possibility of detecting by means of pulsed infrared thermography with an optical source of thermal stimulation any defects in the form of delamination in a multilayer structure, a computer simulation model of a composite made of GFRP (Fig. 2) was subjected to simulation. The model consisted of four layers of fiberglass fabric, having a thickness of 0.09 mm, glued by epoxy resin layers having a thickness of 0.03 mm and it was assumed that each resin layer had a defect in the form of delamination of a thickness of 0.02 mm from air-filled areas of 10×10 mm each.

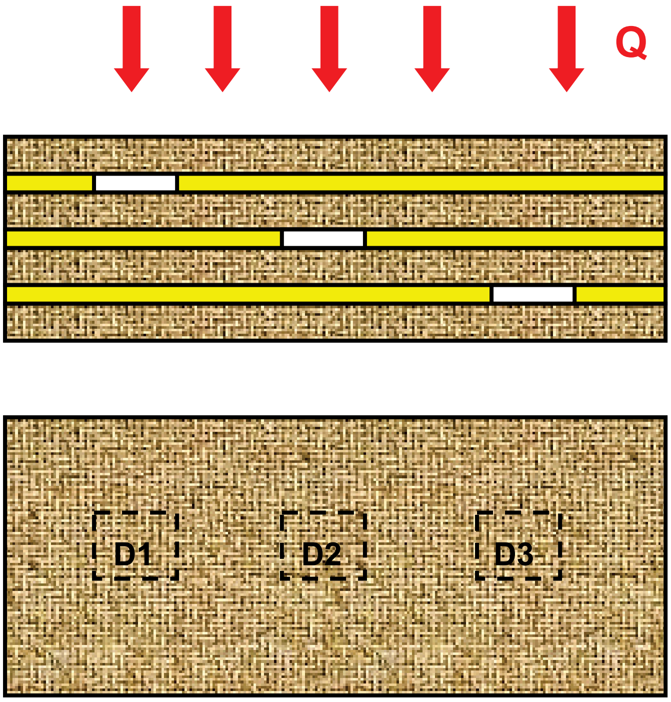


Fig. 2. Model of composite sample with defects

The composite sample was tested using a one-sided testing method; the sample was heated on the front side. For the heating, thermal stimulations with the characteristics shown in Fig. 1 were used. The maximum value of heating power density was, for a single square-pulse heating, equal to $Q_m = 2 \cdot 10^6$ W/m^2, for a single harmonic pulse heating, $Q_m = 2 \cdot 10^5$ W/m^2, heating time for a square pulse was $\tau_h = 0.01$ s and, in the case of a thermal pulse, it was $\tau_h = 0.1$ s. The total time of all simulations was 20 seconds. The simulation parameters were selected so that the maximum temperature of the heated surface of the composite sample was comparable for both simulations and did not exceed the sample destruction temperature (100°C).

Table 1 presents the thermal parameters of composite materials used in the computer simulation.

Tab. 1. Thermal parameters

Material	Heat Capacity [J/kg·K]	Thermal conductivity [W/mK]	Density [kg/m^3]
GFRP	600		2540
fibres direction (‖)		0.38	
fibres direction (⊥)		0.3	
Epoxy resin	1000	0.18	1200
Air (thin gaps)	1005	0.07	1.2

3. Results

The optimum conditions for detection of defects D1-D3 in the simulated composite specimen are shown in Tab. 2. The values of the maximum contrast C_m and the temperature signal ΔT_m are presented for the optimal observation time τ_m (τ_m – the time in which the current contrast value is maximum).

The value of the maximum contrast was calculated in accordance with the following formula:

$$C_m = \frac{\Delta T_m}{T_{ref}}, \tag{3}$$

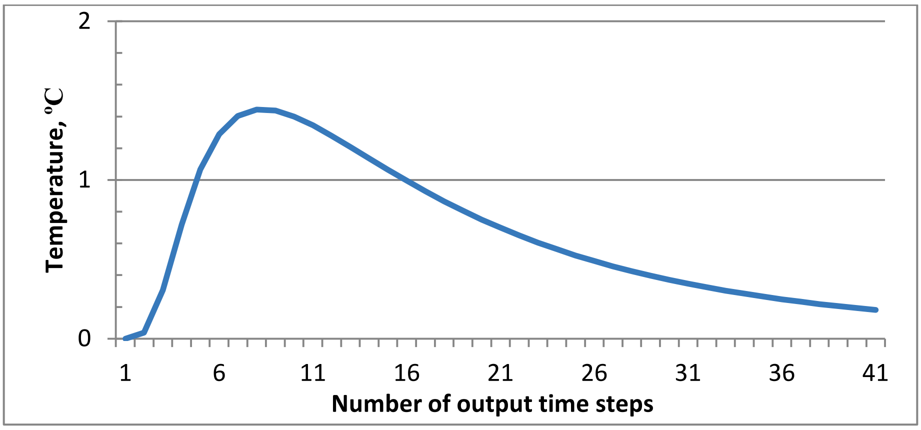
Tab. 2. Simulation results

Thermal excitation	Defect	ΔT [ºC]	τ_m [s]	C [%]
Square-pulse	Defect 1	1.41	3.55	16.8
	Defect 2	0.19	13.66	5.7
	Defect 3	0.04	20	1.9
Cosine-pulse	Defect 1	2.18	5.08	27.1
	Defect 2	0.76	17.72	14.7
	Defect 3	0.11	20	3.9

where:

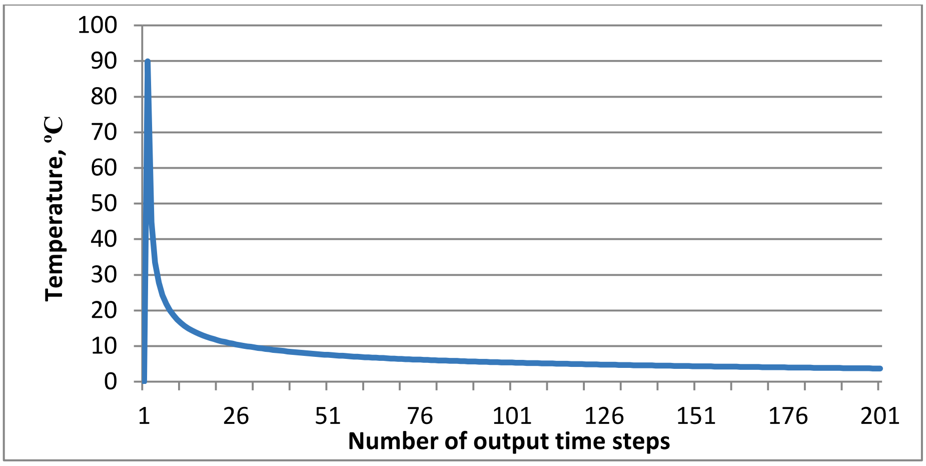
$\Delta T_m = T_{def} - T_{ref}$;
T_{def} – temperature on the surface of the sample over the defect;
T_{ref} – temperature on the surface of the sample at the selected point outside the defect.

Selected simulation results are presented in Fig. 3-5. Fig. 3 presents the course of changes in the surface temperature signal of the sample over the defect D2 heated by a single square pulse. Both the course of changes in the heating and the cooling phase are presented. The nature of the change in the maximum temperature signal on the surface heated by a harmonic pulse without a defect is shown in Fig. 4. Fig. 5 presents the changes of the temperature signal on the surface of the sample over the defect D2 during heating with the harmonic pulse and in the cooling phase.



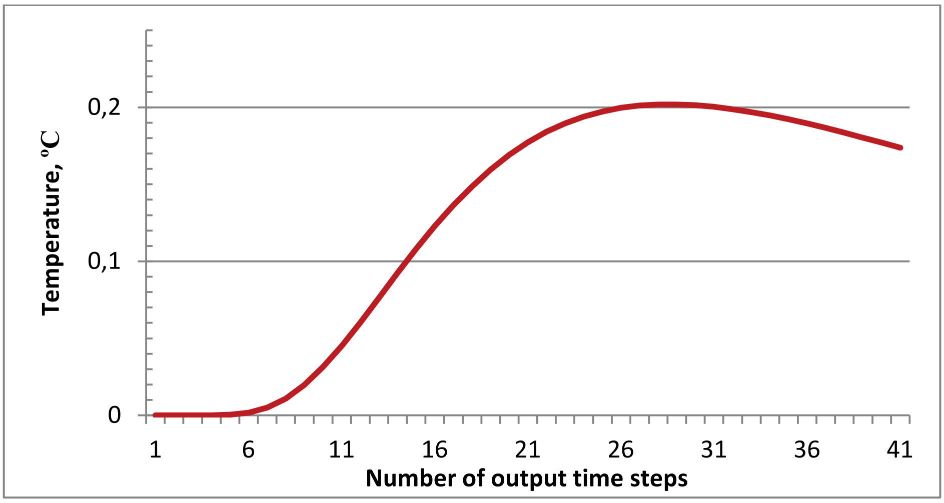
Output time step 0.5 s

Fig. 3. Temperature signal of the sample over the defect D2 heated by a single square pulse



Output time step 0.1 s

Fig. 4. Temperature signal on the surface heated by a harmonic pulse without a defect



Output time step 0.5 s

Fig. 5. Temperature signal on the surface of the sample over the defect D2 during heating with the harmonic pulse

4. Conclusions

Analysing the results it was found that with thermal excitation of the harmonic impulse, all defects could be reliably detected. With the use of a thermal impulse in the form of a square pulse, the detection of the innermost defect is problematic. Much better (larger) temperature differences on the surface above the defects were obtained using a harmonic thermal pulse. The thermo-physical parameters of GFRP are not favourable for the heat flow in the material; therefore, it is difficult to detect very thin defects located deeper under the surface of the material. In addition, the times at which the best conditions for detecting defects are found are relatively long. They can be shortened by increasing the density of the pulse heating the surface of the sample under test; however, it is then necessary to remember the temperature limit regarding destruction of the sample surface.

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