https://www.proconference.org/index.php/usc/article/view/usc30-00-010
DOI: 10.30888/2709-2267.2025-30-00-010

UDC 699.88

THERMOGRAPHY-BASED MONITORING OF REINFORCED COMPOSITES

Pysarenko A.M.
c.ph.-m.s., as.prof.
ORCID: 0000-0001-5938-4107
Odessa State Academy of Civil Engineering and Architecture,
Odessa, Didrihsona, 4, 65029

Abstract. *The aim of this work is to modify the thermographic method for describing the anisotropic structure of reinforced composite materials. The modification of the technique concerned the features of taking into account fluctuations in the temperature field on the surface of the material, for the case when a thermal or external source is used as a stimulating factor. Dispersive analysis of thermal data allowed us to scale the damage development of the bulk structure of the reinforced composite and to study the damage phenomenon from both mechanical and energetic points of view. Thermographic data analysis was performed for the surface of composite samples, the boundary conditions of which corresponded to a fixed static and dynamic tensile load. Dispersive analysis of thermal data allowed to scale the development of damage to the volume structure of the reinforced composite and to study the damage phenomenon from both mechanical and energy points of view. In particular, one of the main problems is to obtain information on the fatigue behavior of composite materials, following the approach successfully applied to homogeneous materials. An approach based on the use of infrared thermography for samples subjected to static or step dynamic loads, which, in turn, correlate with the fatigue strength of the material, was developed. The analysis of the accuracy of the method and the available experimental data indicates the reliability of the presented thermographic methods for studying damage to composites and their fatigue behavior.*

Key words: *thermographic method, temperature field, reinforced composites, dispersive analysis, fatigue behavior.*

Introduction.

Infrared thermography allows non-contact measurements of surface temperature changes of a reinforced composite sample [1]. This method can be used in passive or active mode. Passive mode is usually applied to materials whose temperature differs from the ambient temperature. Active mode must be accompanied by an external stimulus to cause a change in surface temperature. The external stimulus can be a mechanical or thermal source. Passive thermography is rather qualitative, while active thermography allows for both qualitative and quantitative analysis. The passive thermographic method allows for detection of damage of various natures on various composite materials, both laminar and reinforced [2].

Bond failure and delamination of fibers and matrix, moisture penetration into honeycomb sandwich materials, surface delamination in adhesive joints, crack-like defects are the main types of defects in reinforced composites. An example of quantitative analysis based on thermography is thermoelastic stress analysis, which is an experimental stress measurement method based on the thermoelastic effect, which is a reversible change in temperature that occurs in a composite sample when it is deformed in an elastic field and due to a change in volume [3]. The thermoelastic effect can be generalized by the experimental thermoelasticity equation, which establishes a linear relationship between the stress state of a homogeneous isotropic material under adiabatic conditions and the change in its temperature:

$$\frac{\Delta T}{T_0} = -K_0 \Delta\sigma, \tag{1}$$

$$K_0 = \lambda / \rho C_p, \tag{2}$$

$$\Delta\sigma = \Delta(\sigma_1 + \sigma_2 + \sigma_3), \tag{3}$$

where: T_0 is the average temperature; K_0 is the thermoelastic constant; λ is the linear thermal expansion coefficient; ρ the mass density; C_p the specific heat at constant pressure; Δσ is the variation of the first stress invariant.

The system of equations (1) - (3) is formulated for a homogeneous isotropic composite material. However, the same system can also be extended to orthotropic materials by considering different thermoelastic constants in each direction due to anisotropy. Indeed, thermoelastic stress analysis, mainly used for homogeneous materials, has also recently found application for orthotropic materials. However, in some cases, such as reinforced composite materials, the thermoelastic constants depend also on the boundary conditions for the temperature and its derivatives on the surface layer. Such a layer is characterized by a frequency dependence, in addition, it damps the thermal waves generated by the heterogeneity regions of the local volume of the composite material. However, surface temperature changes in materials occur not only due to the thermoelastic effect, but also due to irreversible transformations (i.e. damage, plastic deformation and microstructural changes).

Thermographic techniques

The analysis of the thermography application technique to static tensile testing in this work was supplemented by taking into account dynamic loads and calculating changes in surface temperature. The calculation results indicate that for the case of fatigue of a reinforced composite specimen, the surface temperature of the loaded specimen tends to reach a constant value. This critical value is characteristic of the corresponding thermal stress level. In addition, the initial thermal response to cyclic (dynamic) loads, i.e. the temperature increase (ΔT) during cycling (ΔN), thus the ratio $\Delta T/\Delta N$, is a typical feature of a reinforced composite and can be related to the applied stress.

Calculations show that the $\Delta T/\Delta N$ values, considered as a function of different applied stresses, present a double linear trend. The intersection between these two lines (i.e. the break point) defines the stress level that has been experimentally found to be close to the fatigue limit. The pattern of the $\Delta T/\Delta N$ trend as a function of the maximum stress amplitude has a pronounced nonlinear character. In addition, a method based on gradually increasing stress amplitudes and on the energy characteristics of thermal stress on the surfaces of a composite sample was analyzed. The processes of heat dissipation, and therefore energy, occur when the material begins to be damaged. This irreversible loss of energy is associated with friction within the material or with the irreversible development of damage. A new digital processing method for assessing the dissipated energy is proposed. This method can be implemented using thermographic systems with blocking.

The method takes into account nonlinear coupled thermomechanical effects during cycling. The dissipated energy is much smaller than the thermoelastic source. To estimate the dissipation energy, a special algorithm is required that separates the dissipated energy from the thermoelastic source and filters the signals, neglecting the background noise. A characteristic feature of this effect is that in the case of gradually increasing thermal stress amplitudes, the dissipated energy shows a bilinear trend. When the temperature amplitude is low, the dissipated energy as a function of the applied thermal stress shows an almost flat trend, thus the energy is not dissipated by irreversible mechanisms.

Then there is a rapid increase in the slope for higher amplitudes of thermal stress. The breaking stress in the dissipated energy trend corresponds to the different behavior in the material damage and indicates the onset of damage in the material subjected to dynamic loads. Thus, it could be compared with the fatigue limit of the material. This analysis was confirmed for carbon fiber reinforced composites. The results of the application of thermographic methods demonstrated the presence of a characteristic value for the fatigue limit (σ_D) for the functional dependencies $\Delta T/\Delta N = f(\sigma)$ at an increased concentration of mechanical defects in local volumes of reinforced composites. The analysis revealed a clear bilinear trend for the functional dependencies $f(\sigma)$.

Summary and conclusions.

The analysis of thermography techniques applied to the detection of mechanical defects in the bulk of reinforced composites points to the relationship between the thermal response and the nature of the damage initiation dynamics and, in particular, the fatigue limit. The calculation results indicate that thermography is an effective method for flaw detection of reinforced composites.

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sent: 18.03.2025