EVALUATION OF SUBSURFACE DEFECTS IN CYLINDRICAL COMPOSITE STRUCTURES USING ACTIVE THERMOGRAPHY

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Abstract

In the present work, experimental and numerical (finite element) results obtained from thermographic analysis of cylindrical specimens made of GFRP are presented. Artificial delaminations were simulated by the direct 3D model, based on non-merged nodes between lamina, on the area of the defects with eight layers of elements in the shell thickness corresponding to eight laminas. For investigated panels, two forms of the defects are studied in details: (1) circumferential and (2) longitudinal. The proposed FE methodology allows to consider the influence of various geometrical parameters characterizing delaminations on the heat flow within the tested structure and its temperature effects on examined surfaces.

1. Introduction

The increasing demand in lowering maintenance costs in engineering structures made of composite materials (e.g. aeronautics) contributes to the growing development of structural health monitoring systems. Such systems would insure continuous knowledge of the structural state of the monitored structural components, possibly allowing directed maintenance and maintenance task optimization. Techniques used to realize the checking must obviously not damage these structures. Many methods have been developed during recent decades, and they have all been grouped under the term of Non-Destructive Testing (NDT) methods, such as: e.g.: mechanical (ultrasonic, acoustic emission), thermal (thermography), magnetic (Eddy current), X-ray (tomography) and visual (penetrant testing, CCD camera). Optical fibre methods [1,2]. Kuhn et al. [3] have been shown and discussed some characteristics of the most common NDT methods used in industry. They noticed the growing interest of optical devices, like CCD and IR cameras, which could extend the limits of defects detection. For this reason, optical devices have been introduced within most of the standard methods, leading to create coupled techniques. For example, laser-ultrasound [4], magneto-optical [5], eddy current-visual [1] and thermosonics [2] are nowadays developed. A number of commercially available SHM systems were assesses with respect to their ability to identify and monitor impact events and damage on composite structures, e.g. VAGILLANT [6] or TATEM [7].

Infrared thermography offers an ideal, cost-effective Non-Destructive Evaluation (NDE) solution for a wide range of in-service and manufacturing composites applications. It is fast, noncontact, can be single-sided, and offers wide area coverage of flat or curved parts. It is used for composite NDE applications, including detection of delaminations, impact damage, water entrapment, inclusions, density variations, and evaluation of adhesive bonds. Thermographic techniques offer the benefits associated with broad area scanning while maintaining the potential for efficient subsurface anomaly prediction capabilities [8,9]. Quantitative infrared thermography as a non-destructive and noncontact technique has been used to detect manifestation of the physical process of fatigue and to evaluate rapidly the fatigue limit of materials or mechanical components [10-13]. R. Ham-Ali et al. [14] used the spatial distribution of temperature gradient measured from the surface to determine the surface strain fields in mechanically loaded orthotropic materials, particularly around the notches. Transient thermography was also successfully employed in the inspection of defects in various aircraft composite panels [15].

In thermographic NDE (TNDE), a surface of the component under test is actively heated, and the subsequent surface temperature response of the part to the stimulation is monitored with an IR camera. Although there are many possible configurations for TNDE (e.g. TT, cooling stimulation, and step or modulated heating, etc.), the same basic principles apply. The physical process can be reduced to three steps in which energy is converted to various forms:

- The surface of the component is uniformly heated. Typically this is accomplished using light, although forced air, steam, hot water, electrical current, electromagnetic induction, and acoustic energy have been demonstrated for particular applications.
- As thermal energy from the heated front surface diffuses toward the cooler interior and back surface of the component, the front surface temperature of the component falls. However, areas of the front surface that are located above subsurface defects (discontinuities in the material density, thermal conductivity, or heat capacity) will cool at a different rate than defect-free areas.
- An image of the surface temperature of the heated component is monitored using an IR camera, which collects IR radiation from the surface of the sample. Defect areas will exhibit anomalous cooling behaviour, which will appear in the infrared IR of the surface.

It is important to understand the energy conversion processes described previously, because ineffective conversion in any of these steps will adversely affect the result. For example, a component with an optically reflective surface will not absorb light efficiently, and may have to be treated with a removable paint or heated using a non-optical source. A material that is a poor thermal conductor will respond to the heat stimulus very slowly, while the image of a sample with poor IR emissivity will be relatively weak.

If many techniques already exist, they still do not give complete satisfaction. For example, a method can give good results but samples must be small, or it does not work with all the materials, or it is difficult to use with high rates of production in industry, etc. In the present paper the analysis is carried out both experimentally and theoretically with the use of the finite element method.

2. General thermo-elastic formulations for orthotropic composites

The thermo-elastic effect refers to the thermodynamic relationship between the change of stress in a component under elastic loading and the corresponding change of temperature. It is simply proportional to the change in the sum of principal stresses, if adiabatic conditions prevail. Combining the first and second principles of thermodynamics the local heat changes can be described by Eq. (1).

$$Q_{i,i} = T \frac{\partial \sigma_{ij}}{\partial T} \dot{\varepsilon}_{ij} - \rho C_{\varepsilon} \dot{T} + \rho \dot{R} \tag{1}$$

where Q_i is the heat flux through the surface whose outward directed normal is n_i; T is the temperature; σ_{ij} is the stress tensor; ε_{ij} is the rate of deformation tensor; ρ is the density; C_ε is the specific heat coefficient at a constant deformation; R is the heat production rate of the internal heat sources per unit mass. Hooke's thermo-mechanical constitutive law for a linear anisotropic material is expressed as:

$$d\sigma_{ij} = C_{ijkl} d\varepsilon_{kl} - C_{ijmn} \alpha_{mn} dT \tag{2}$$

where C_{ijkl} is the fourth rank tensor of the material constants; α_{mn} are the coefficients of thermal expansion and dT is the change in temperature. If the thermo-mechanical material properties are assumed to remain constant with change in temperature, then the stress change with temperature is simply

$$d\sigma_{ij} = -C_{ijmn} \alpha_{mn} dT \tag{3}$$

Combining Eqs. (1) and (3) and assuming adiabatic conditions with no internal heat sources ($Q_{i,i} = 0$, and $\dot{R} = 0$) yield:

$$\rho C_{\varepsilon} \frac{\dot{T}}{T} = -C_{ijmn} \alpha_{mn} \dot{\varepsilon}_{ij} \tag{4}$$

Next, assuming small strain theory, and using the incremental form of Hooke's Law, Eq. (2), to express $C_{ijkl} d\varepsilon_{kl}$ in Eq. (4) yield:

$$\rho C_{\varepsilon} \frac{dT}{T} = -\alpha_{mn} \left(d\sigma_{mn} + C_{ijpq} \alpha_{pq} dT \right) \tag{5}$$

The numerical capabilities offered by finite element modeling (FEM) were once limited to structural analysis. The ability for FE to adequately simulate and reconstruct stresses and strains on loaded structures has been a compelling force in furthering the understanding of structures both micro and macroscopically. This same elevation in research can now be applied to thermal mechanics described e.g. by Eq. (5). It has been show in studies performed [16] that 3D finite element modeling of the thermographic technique considers aspects of thermal modeling that go unaccounted for when compared to 1D and/or 2D numerical methods. And while the importance of such differences may not be inherently obvious when considering subsurface defects in flat panel composites, the nature of the problem becomes significant when simulating thermal behaviour in complex components.

3. Finite element modeling of structures with an artificial delamination

Nowadays the finite element method is usually applied in the analysis of various engineering problems. The FE NISA II package was frequently used to evaluate dynamic behaviour of composite structures. In the present study the 3D solid finite element type with a 20 nodes was used in modelling a structure. A higher order version of a classical 8-node solid element with three degrees of freedom per node allows us to obtain accurate results of the analysis. Delamination, being a debonding of neighbourhood plies in composite laminates, is the most common and danger defect which may originate during fabrication or utilization of a structure under out-of-plane stresses or subjected to transverse impact. In this study from several methods of modelling of delamination the direct model based on non-merged nodes between lamina on area of the defects was used (Fig. 1) with eight layers of elements in the shell thickness corresponding to eight lamina. A surface contact algorithm was introduced to process the contact problem arising from delamination, primarily relaxing restrictions on two contactable surfaces.

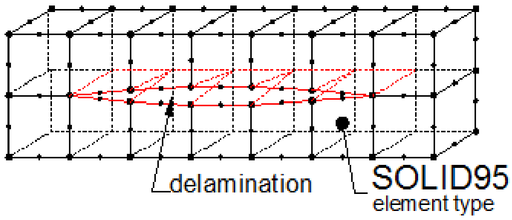

Figure 1. The finite element model of the delamination

For composite cylindrical shells/panels two forms of the delamination cracks are studied in details (Fig.2):

- circumferential delamination where the length parameter $a=\alpha/L_{circumf}$ is variable, and the length in the longitudinal direction a is a constant and equal to the length of the shell L,
- longitudinal delamination where the length parameter a/L is variable, and the length in the circumferential direction α is a constant and equal to the length of the shell $L_{circumf}$.

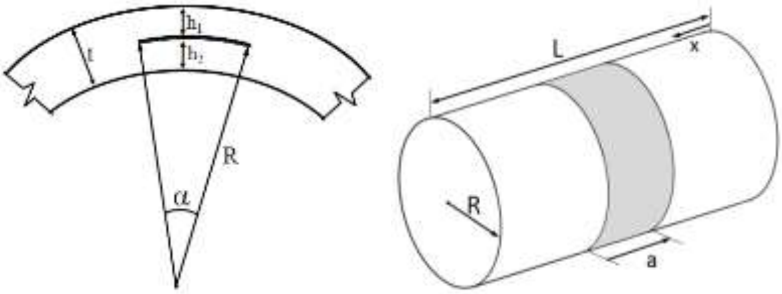

Figure 2. Geometry of a cylindrical shell with delaminations.

The analytical solution of the static problem is presented in Ref. [17]. A thermal pulse of 1000 J applied via a flash tube lamp upon one surface of a composite laminate while temperature is monitored by an infrared analyser. The test included defects embedded within the slab plane of symmetry of a 2 mm thick composite slab (t = 2 mm). Each defect was represented by one film of 0.25 mm thick square Teflon inclusions (to simulate an air delamination), and were varied in edge size – Fig. 2. The results of the numerical computations are shown in Figs 3 and 4. Note that these graphs utilize a normalized time to maximum contrast (t_m^*) and maximum contrast at t_m^* (ΔT_m^*) in relating subsurface information where:

$$t_m^* = \frac{\xi t_m}{t^2}, \Delta T_{max}^* = \frac{\Delta T_{max}}{T_{0max}} \qquad (6)$$

t is a shell thickness (Fig. 2), î denotes diffusivity, t_m means the maximum inflection time, and T_{0max} represents a situation without any heat loss for a purely resistive defect

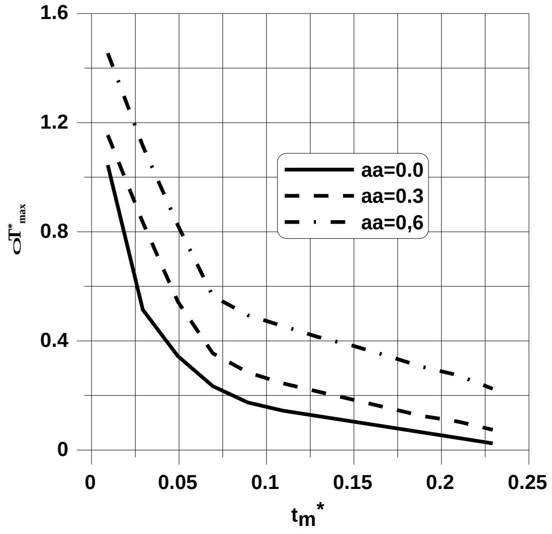

Figure 3. The comparison of results for circumferential delamination.

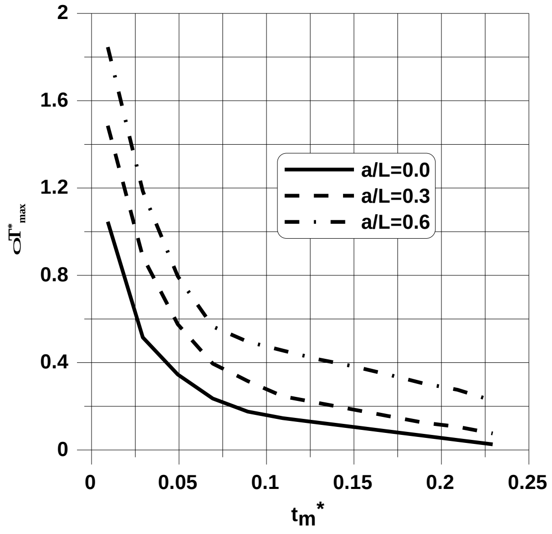

Figure 4. The comparison of results for longitudinal delamination.

The magnitude and the form of the delamination affect the heat flow. In general, it is reduced as the delamination length increases. Since the analysis have been conducted for the shallow cylindrical panels having the length L=300 mm, the radius R=100 mm the heat resistance effects are much more evident for longitudinal delaminations although the dimensionless parameters a/L and aa are identical.

Using the proposed methodology of the FE method it is also possible to consider the influence of various geometrical parameters characterizing delaminations on the heat convection, however, due to the lack of space those problems will be discussed later.

4. Experimental analysis

The system used in this trial has two flash lamps, which are mounted within a hood along with a Flir 235 camera. The flash lamps are triggered after which the camera records a series of thermal images of the surface. This data is then processed with the use of the IRNDT system to facilitate review with a suite of sophisticated analysis tools. Fig. 5 shows the test bench developed for the thermography tests for which halogen lamps are used to illuminate the sample, either for a short time with high intensity flashes or for a longer time but with lower intensity lighting. In both cases, optical waves impact the sample, and where there is a defect, the energy level does not change at the same velocity than the one measured for a healthy area.

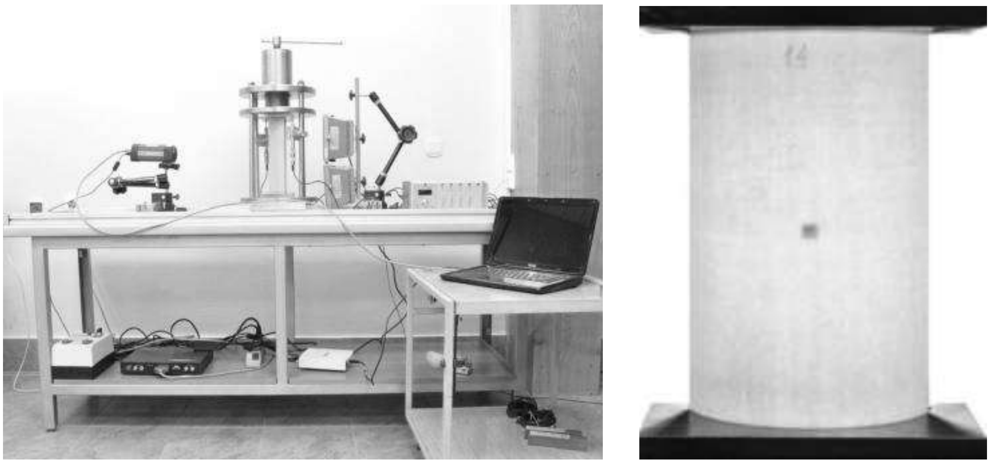

Figure 5. Experimental equipment for thermography tests.

The material studied is a composite woven roving glass/ epoxy resin. The elastic behaviour of an anisotropic composite material is described by a four material constants, i.e. the Young modulus $E_1=E_2=62$ [GPa], Poisson’s ratio $\nu=0.26$ and the Kirchhoff modulus $G_{12}=7.8$ [GPa]. The broad discussion of the experimental results is demonstrated in Refs [18, 19, 20] and we shall not dwell on it herein.

6. Conclusions

The numerical modeling of subsurface defects allows more precise prediction capabilities. What is also important is that more precise experimental data is needed to render defect prediction realistically possible. This enhances the requirement for refinement procedures and signal-to-noise ratio improvements in order for clean contrast evolutions to be obtained from thermographic data.

The use of Teflon and other artificial inserts to represent cavities in composite material, while an established procedure regarding structural analysis, is unsuitable for thermal analysis. Together with a micro-structural analysis into the very nature of delaminations and subsurface defects in composites, the ability to predict such anomalies will become clearer.

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