PREDICTION OF SUBSURFACE DEFECTS THROUGH A PULSE THERMOGRAPHY; EXPERINENTS VS NUMERICAL MODELING

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Abstract

The present study deals with the experimental and numerical (finite element) investigations of a cylindrical laminated panel behaviour subjected to compression and having a single square delamination. The use of infrared transient pulsed thermography provided excellent results on possibility of the detection of the insert thickness and of cracks occurring at the final failure of the structure for all investigated samples. In the numerical, finite element investigations the influence of the thickness insert on the thermal conductivity is studied. The computed buckling envelope demonstrates the influence of the mechanical compressive loads and thermal effects arising during the heating process during the thermographic analysis.

1 Introduction

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 [1,2]. Quantitative infrared thermography as a nondestructive 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 [3-6]. R. Ham-Ali et al. [7] 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 [8]. Recently, for monitoring damage in composite materials thermography was used commonly with other ND techniques such as e.g. thermosonics [9] or acoustic emission [10]. The ability to predict subsurface defect information in composite materials through a non-invasive thermography should be combined with the detailed theoretical and numerical analysis as it is pointed out e.g. in Refs [11-15]. The aim of the present study is to detect: (1) defect depth/thickness effects, (2) defect size effects. A compressed composite cylindrical multilayered panel having a single square delamination is considered in details - see Fig.1. The use of Teflon and other artificial inserts to represent cavities in composite material,

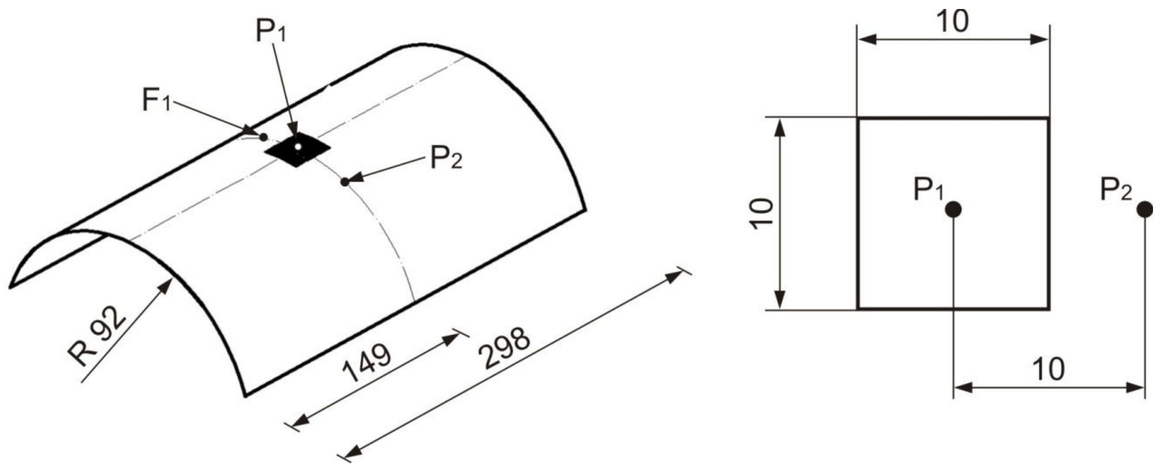


Figure 1. The geometry of analysed composite structure.

2. Experimental Procedure and Results

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. 2 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.

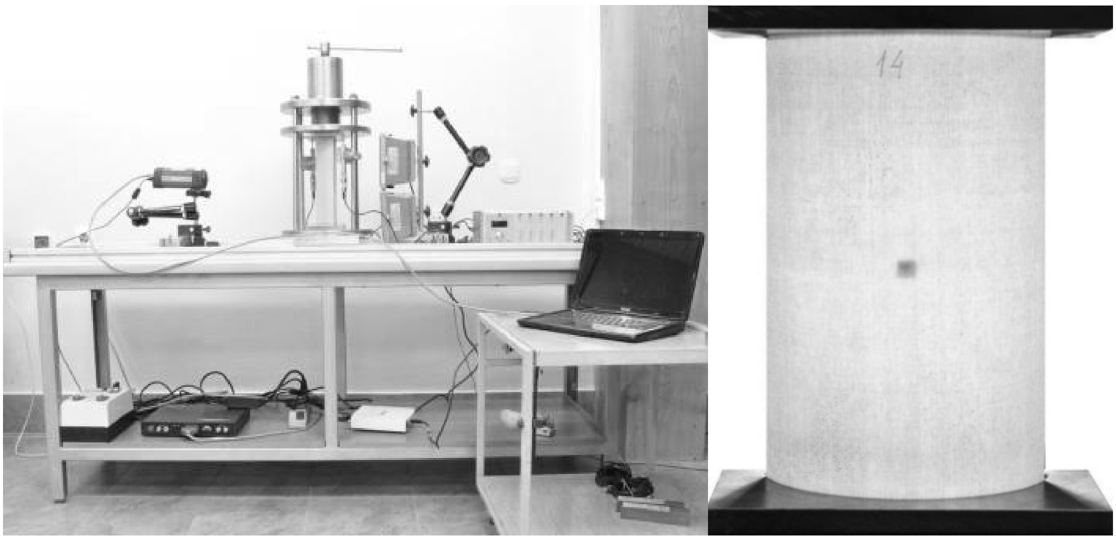
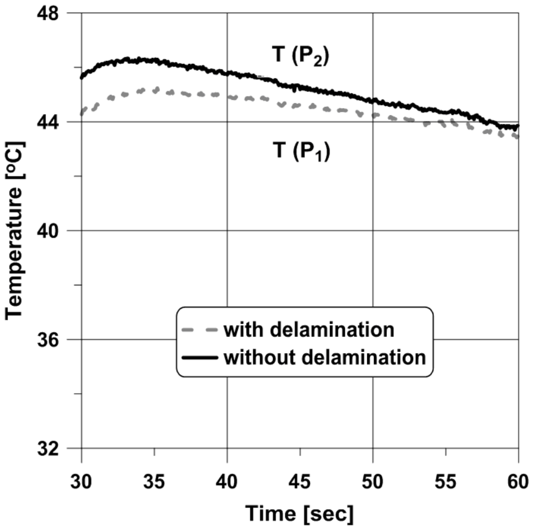
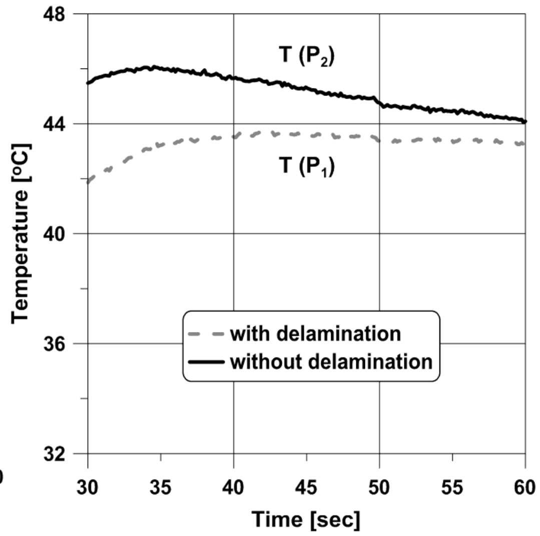


Figure 2. Experimental equipment for thermography tests.

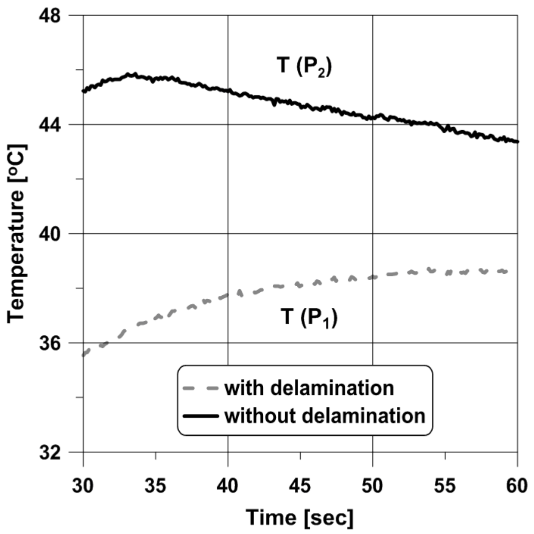
The material studied is a composite woven roving glass/ epoxy resin. The elastic behaviour of an anisotropic composite material is described by a four material constants, i.e. the Young modulus E_1=E_2=62 [GPa], Poisson's ratio ν=0.26 and the Kirchhoff modulus G_{12}=7.8 [GPa]. The research concerned in this study involves the investigation of one particular technique known as pulse phase thermography (also referred to as flash/pulse thermography). PPT involves rapidly heating the surface of a sample and observing the decay of heat on that, or the opposite surface using a camera. The camera detects interruptions in the normal heat transfer of the applied energy and displays these differences as a contrast to normal thermal flow under these conditions. The detection of the temperature differences was observed at two points P_1 and P_2 presented schematically in Fig.1. The analysis was carried out under various loading condition since the cylindrical panel was uniformly compressed in order to investigate the possible opening of the delaminated area. The first objective in this study was to make a correlation between the changes of the temperature of specimen and the thicknesses of the Teflon inserts, denoted by the symbol t_i. Figs 3 a, b and c demonstrate the distribution of the temperature with time at two points. The heated surface is localised in the delaminated area – Fig.1. As it is shown in Fig.4 the correlation of the measured temperatures for various specimens is quite good.



a) t_i=0.2 [mm]



b) t_i=0.7 [mm]



c) t_i=1.2 [mm]

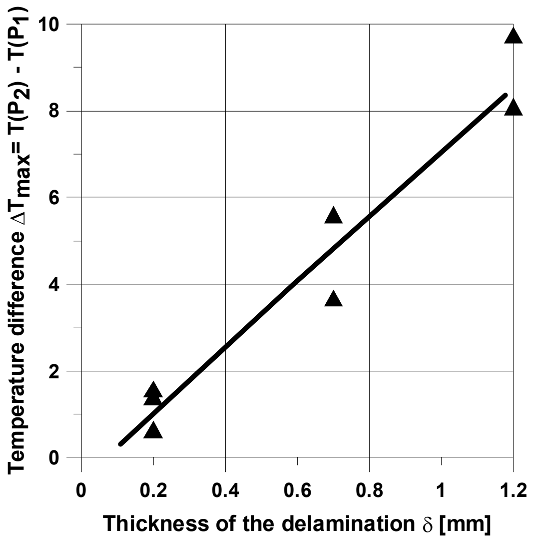


Figure 3. Distributions of temperature variations in the cooling stage

Figure 4. Differences of temperature measured for various specimens

The identical effects to those plotted in Figs 3 and 4 were observed for different values of the compressive forces but prior to final failure of the laminated structures that took the form of classical cracks but preceded by the global buckling of the cylindrical panel. The buckling mode as well as the final failure form of the panel is presented in Fig. 5. It is worth to mention that both the buckling loads and modes are insensitive to the existence of the delaminated area. In addition, the area of delaminated surface was not changed up to final failure, independently on the thickness of inserts. However, the delamination affects on the final failure form of the composite panel – Fig. 5.

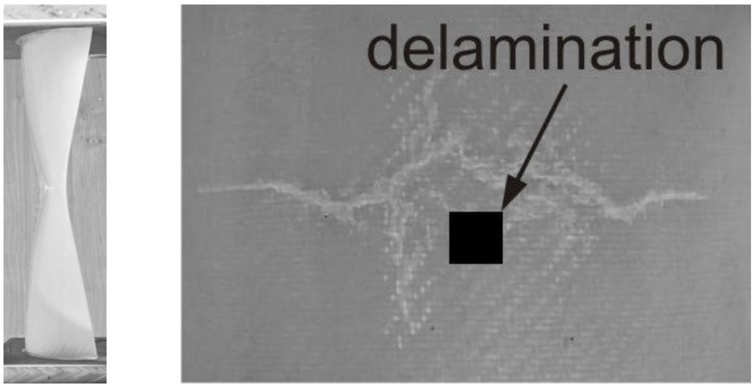


Figure 5. Buckling mode and failure of cylindrical panels.

A pulsed thermographic system (thermoscope) was used not only to image the defects but also to present their evolution under the various loading conditions. Increasing the value of compressive load the variations of the temperature at the point F_1 (Fig.1) was also detected. As it may be seen in Fig.6 the distributions of the temperature decrease with the increase of the damage. They are obtained for different loading conditions represented by the values of displacements of boundary plates (Fig.1) measured in mm.

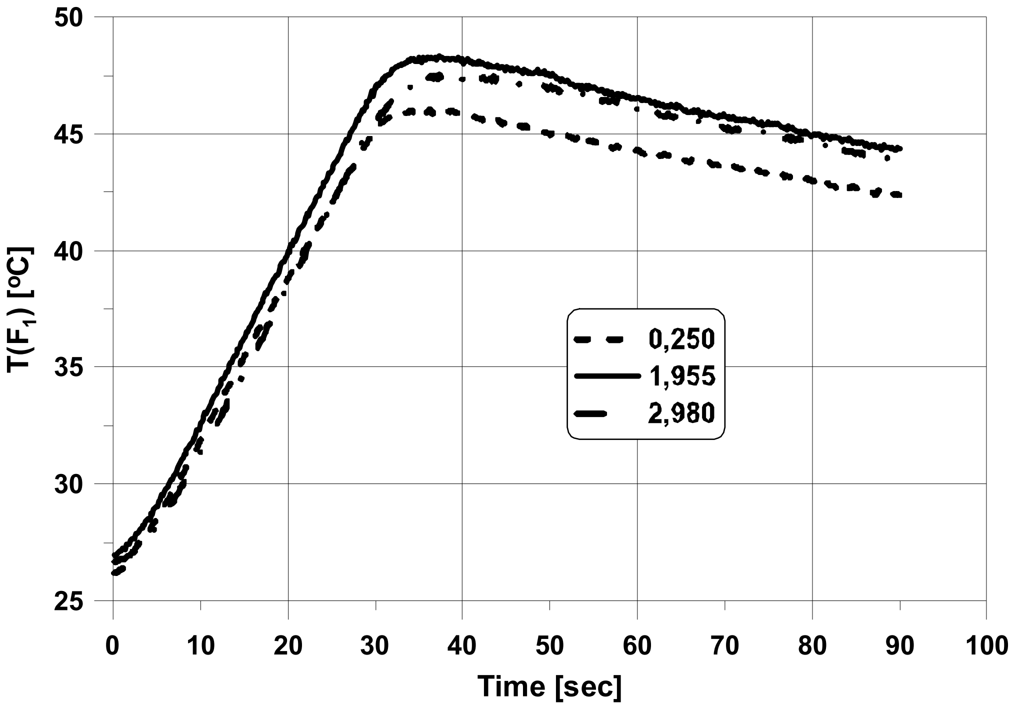


Figure 6. Distributions of the temperature variations at the point of damage (crack) F_1

3. Numerical (Finite Element) Analysis

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. It has been shown in studies performed that 2D or 3D finite element modeling of the pulse thermographic technique considers aspects of thermal modeling. The numerical analysis may be conducted in order to predict the heat flow (Fig. 7), the temperature distributions across the thickness of the laminated composite as well as the stress and strain distributions during loading boundary conditions including both mechanical and thermal loads. The numerical analysis is carried out with the use of the FE package NISAII v.17.

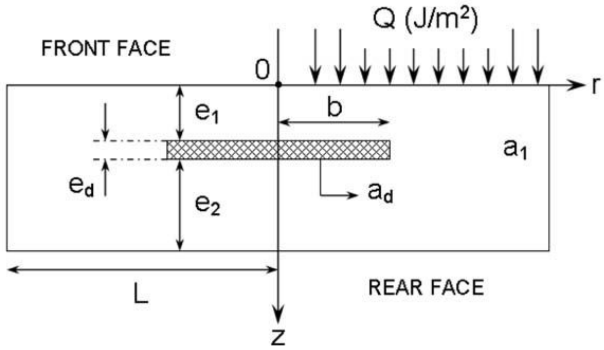


Figure 7. Modeling of the heat flaw

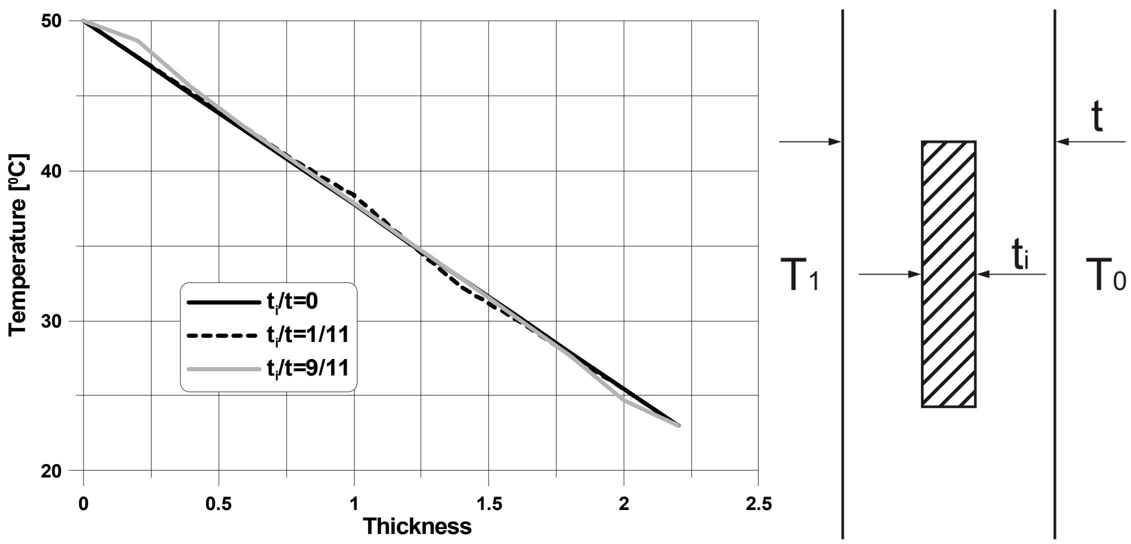


Figure 8. Temperature distribution along the shell wall with prescribed boundary conditions

3.1. Heat Conduction in a Delaminated Area

The shell wall was modeled with the use of the plane for node elements. The Teflon insert has the thermal conductivity coefficient equal to 0.1 [W/^{0}Cm], and the composite – 0.3 [W/^{0}Cm]. The shell wall was divided into 11 equal parts. All nodes at the inner part (heated by the halogens) are specified at the temperature equal to T_1, whereas at the outer part are specified at T_0. The temperature distributions along the shell thickness are plotted in Fig.8. The distribution of temperature is a linear for specimens with no delamination insert. However, the Teflon inserts do not change drastically the mentioned linear distribution, independently on the thickness of inserts.

3.2 Linear Buckling Analysis

During the experiments it was noticed that prior to mechanical buckling under compression the heating of the shell surface resulted in the appearance of the buckling failure or the final damage in the form of cracks – Fig. 5. Therefore, in the FE studies it is necessary to consider both mechanical and thermal loading. To model it in the way convenient for the thermographic analysis the shell was loaded by the mechanical compression and the the temperature increased up to the buckling failure. In the FE analysis quadrilateral four node shell elements was used. The obtained buckling envelope takes the triangular form as it is plotted in Fig. 9. Of course, in the linear buckling analysis the final buckling does not depend on the loading path.

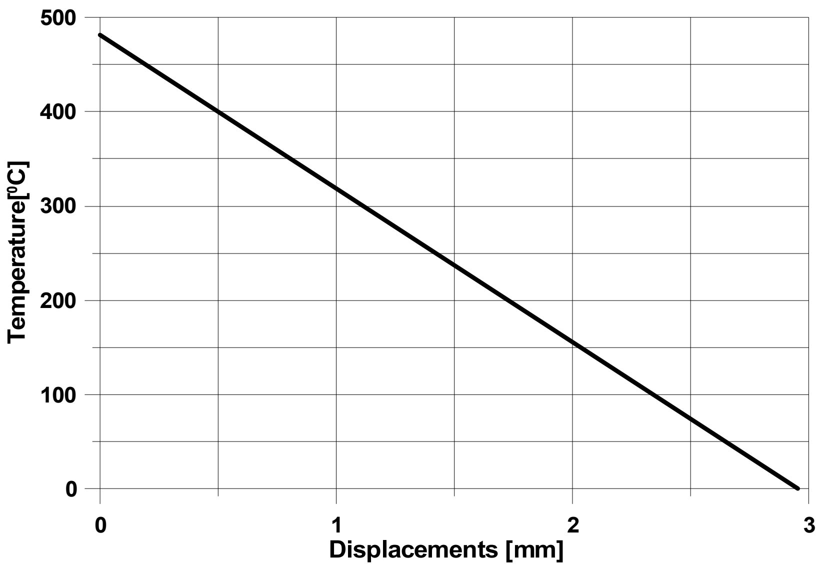


Figure 9. Buckling envelope for thermal and compressive loading

It is worth to mention also that the buckling envelope plotted in Fig. 9 is identical for cylindrical panels with and without delamination.

4. Conclusions

The main objective of this research work was to examine the effectiveness of transient thermography to detect a delamination defect in cylindrical panels. Infrared thermography provided excellent results on all investigated samples. A nomogram is presented that illustrates the influence of the delamination thickness on the observed differences of measured temperatures. The experimental results demonstrate that the analyzed delamination does not expands during compressive mechanical loading up to the final failure. Such a conclusion is confirmed by numerical, finite elements studies. The numerical analysis shows that the temperature distributions inside the shell wall is insensitive to the variation of the Teflon insert thickness. However, such a situtuation may be changed if the difference in the thermal conductivies between two materials is noticeably large. The buckling envelope for the thermal and compressive loading is also demonstrated. It has a triangular form.

Acknowledgment

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