International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:10, No:3, 2016

Thermographic Tests of Curved GFRP Structures with Delaminations: Numerical Modelling vs. Experimental Validation

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Abstract**—**The present work is devoted to thermographic studies of curved composite panels (unidirectional GFRP) with subsurface defects. Various artificial defects, created by inserting PTFE stripe between individual layers of a laminate during manufacturing stage are studied. The analysis is conducted both with the use finite element method and experiments. To simulate transient heat transfer in 3D model with embedded various defect sizes, the ANSYS package is used. Pulsed Thermography combined with optical excitation source provides good results for flat surfaces. Composite structures are mostly used in complex components, e.g., pipes, corners and stiffeners. Local decrease of mechanical properties in these regions can have significant influence on strength decrease of the entire structure. Application of active procedures of thermography to defect detection and evaluation in this type of elements seems to be more appropriate that other NDT techniques. Nevertheless, there are various uncertainties connected with correct interpretation of acquired data. In this paper, important factors concerning Infrared Thermography measurements of curved surfaces in the form of cylindrical panels are considered. In addition, temperature effects on the surface resulting from complex geometry and embedded and real defect are also presented.

Keywords**—**Active thermography, finite element analysis, composite, curved structures, defects.

I. Introduction

THE constant development of engineering constructions is dependent on the creation of new, hitherto unique composite materials but also their reliable and cost-effective inspection both manufacturing process and further operation. Composite materials are prone to numerous modes of failures, such as fiber breakage, fiber debonding, matrix cracking and the most frequent which is delamination. These failure mechanisms can interact and develop, significantly lowering properties of the structural components. Additionally, there is high probability, that in many cases subsurface flaw remains undetected, which can result in the risk of the human health or life. Therefore, there is highly desirable demand for development of the Thermal Non-Destructive Testing methods (TNDT).

Infrared thermography has been successfully applied for the detection of hidden corrosion in metallic plates [1], cracks in ceramics [2] and metals [3], disbonds in reinforced concrete [4]. Numerous works can be found in literature concerning composite materials like fiber metal laminates [5], shape adaptive structures [6] or sandwiches [7]. However most interesting field concerns defect detection and its quantification in high-performance application like aircrafts [8], [9]. Most studies are concentrated on evaluation of defects such as delamination in composite plates [16], [17]. IRT has been also applied to the study of fatigue behaviour of isotropic: steel [10] and aluminium specimens [11] or for the determination of the high cycle fatigue strength of woven composite laminates under tensile and compressive loadings [12], [13]. It should be also noted that there were also attempts to measure and characterize artificially damaged composite structures subjected to cyclic loads [14]. In particular, it is worth to mention about studies on residual fatigue life assessment of glass fibre reinforced composites with delaminations [15].

There is steady increase of extending the limits of defects detection. For this purpose, optical devices have been introduced within most of the standard nondestructive methods, leading to create coupled techniques such as, laser-ultrasound [18], magneto-optical [19], eddy current-visual [20] and thermosonics [21] are nowadays developed.

It is also clear, that the use of numerical modeling and its further comparison to experimental data provides a unique opportunity to study the particular effects on thermal behaviour of investigated object what change current understanding of IRT. Examples can be found in [22], [23].

Active thermographic methods, e.g. pulse, lock-in, pulse-phase procedures, showed their usefulness in detection and evaluation of defects occurring in plates but their application to complex geometries is not widespread. This study is focused on possibilities of the use of the AIRT for thermal behaviour characterization of the multilayered curved composite components with delaminations. As a result of this work, a parametric FE model was calibrated and validated experimentally.

II. Active Infrared Thermography (AIRT)

Infrared thermography also known as thermal imaging is the process that allows to convert emitted infrared radiation into temperature values. Moreover, it includes further signal processing, its visualization, computation and analyses of the temperature patterns.

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Methods of the infrared nondestructive testing can be divided into active and passive techniques. The difference between them consist in the origin of the infrared radiation emitted by the investigated surfaces. In the first case, the investigated material does not require external supply of energy, unlike active procedures which need additional stimulation (e.g. heat) [24]-[27].

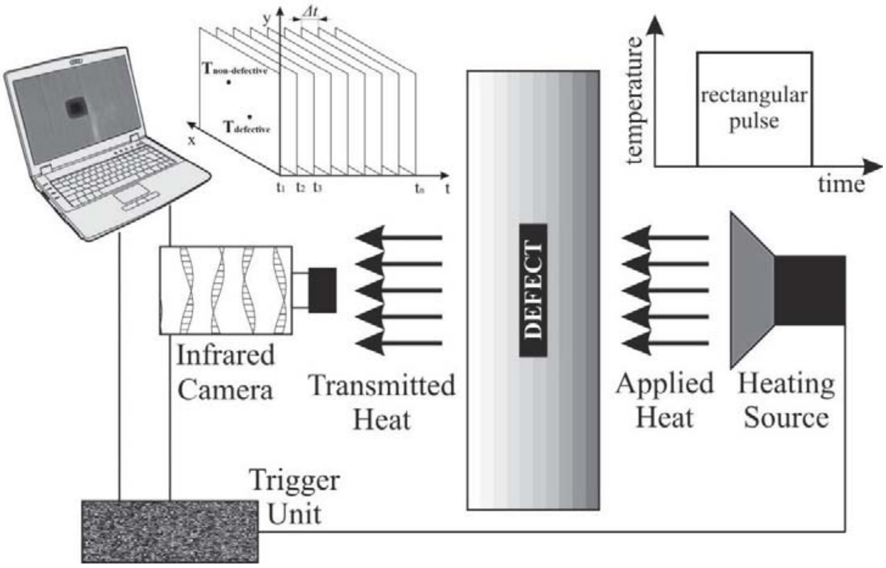

Fig. 1 Principle of the Pulse Thermography

Passive thermography employs the temperature of the examined object during its normal operation or immediately after the end of its work to detect undesired deviations, when temperature contrast on the surface may indicate a possible damage. Defects radiate or absorb the heat resulted from the mechanical or thermal loads, occurred during the operation of examined object, so they can be identified by passive methods. Advantages of this configuration is direct on-site interpretation of the results without additional instrumentation.

Active Infrared Thermography is based on monotonic or periodic supplying of external energy to the investigated object. In order to reveal hidden flaws by this type of methods, dynamic temperature field (heating or cooling) is generated. This procedure is caused by equal temperatures of the defective and healthy (non-defective) areas of examined material during steady state, therefore it is necessary to excite it. Depending on the form and quantity of supplied energy, AIRT can be distinguished into following approaches: Pulse Thermography (PT), Lockin Thermography (LT) and Vibrothermography (VT).

The pulsed IRT is currently the most popular among others AIRT approaches due to its quickness of inspection and ease of deployment in the field measurements and data interpretation. It uses an energy excitation source to rapidly induce the surface of the investigated material, then, an infrared camera records series of thermograms at constant intervals in time domain, both during heating and cooling stages. When the thermal waves reach the defect, it changes its propagation rate, producing thermal contrast on the surface. Pulsed thermography is an indirect process because subsurface features of a material are inferred by the surface temperature response. It should be noted that the pulse period must be chosen carefully to prevent failure of an analyzed material. Results are visualized throughout creation of thermal images (thermograms) sequence which maps the temperature distribution on the surface of the examined object in time domain. This process is schematically illustrated in Fig. 1. Among broad possibilities of pulsed thermography application, it is also important to determine the limitations of this method caused by research equipment and investigated objects.

It should be noted that arrangement of the heat generator and recording equipment could be done by two schemes: one and two sided (in reflection or in transmission). It has influence to the measurement in point of view of practical application. For example, in many practical cases the transmission method cannot be applied due to inaccessibility of back surface. Reflection configuration allows to provide information about defect depth but only near the investigated surface in contrast to two sided method, which is on the other hand able to reveal deeper defects [24]-[27].

Subsurface anomalies occurring in the investigated objects are identified due to their temperature representation on the surface. Basic and mostly used measure of defects is the temperature difference between pre-selected reference area which is assumed to be non-defective and the defective area. This temperature difference is called in TNDT&E nomenclature as an absolute thermal contrast C_a. It was schematically illustrated in Fig. 2.

Broader considerations of the issues presented in this paragraph connected with fundamentals of AIRT can be found, e.g., in [28]-[30].

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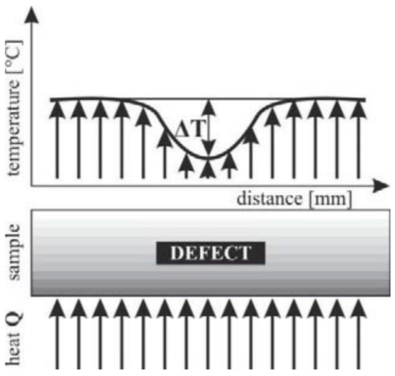

Fig. 2 Absolute thermal contrast C_a

III. Numerical (Finite Element) Modelling

Prediction of the thermal behavior of the investigated object can be established analytically and/or numerically. The first case is restricted to some ideal cases with simple shapes, selected boundary conditions and isotropic materials without defects. In practice, numerical methods are used more often due to their possibilities of solving problems concerning nonlinear phenomena, 3D complex geometries, any boundary conditions, anisotropic materials, etc. Two most popular numerical approaches in engineering are: Finite Difference Method (FDM) and Finite Element Method (FEM).

FEM offers capabilities to better understanding of thermal processes, which are the basis of thermographic analysis. The numerical investigation can be conducted in order to simulate the heat flow through the material as well as the stress and strain distributions during loading conditions including both mechanical and thermal loads.

A. Description of FE Model

In the present work, transient heat transfer analysis were performed for 3D model with embedded various defect sizes in order to investigate their influence on thermal behavior of curved composite panel. Examined specimens were analyzed using commercially available numerical ANSYS package.

Fig. 3 shows schematically boundary conditions and Fig. 4 shows finite element mesh used in this analysis. It was assumed that the investigated specimen was in equilibrium with the environment at the beginning of the analysis, therefore measured ambient temperature in the laboratory (T_{amb}=27°C) was used in the numerical model both as a boundary and as initial conditions. Convective coefficient corresponds to value recommended in literature for natural convection in still air environment ($5<h<10$) [31]. The density of the heat flux was adjusted to the experimental results.

SOLID90 3-D high order thermal solid element was used in current investigation. This element has 20 nodes with a single degree of freedom; temperature at each node. It has compatible temperature shapes and is well suited to model curved boundaries.

Thermophysical properties of materials used during modelling, which were either taken from literature or values specified by producer of investigated material [32], [33].

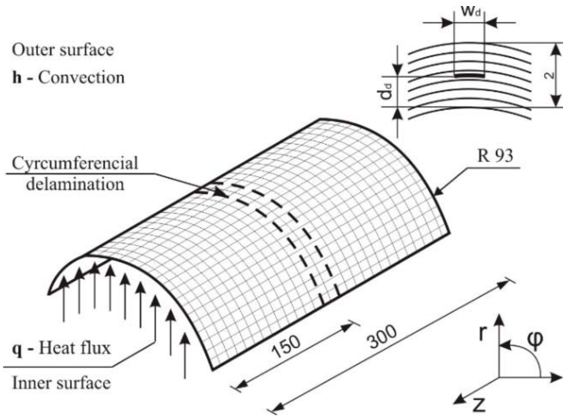

Fig. 3 Geometry of specimen, boundary conditions of the 3D numerical model and the location of the artificial delamination


Fig. 4 Example of finite element mesh

All simulations were carried out in two sided procedure i.e. heat flux was applied on the rear surface and front surface was observed both heating and cooling stages. Entire thermal analysis similarly like in experiment last 100 s and consists of two load steps. In the first part, ideal stepped pulse with amplitude equals 7800 W/m^2 for time duration equals 10 s is instantaneously applied, while front surface is cooled by natural convection. It is assumed that heat pulse has ideal rectangular shape and heat flux is uniformly deposited on a rear surface of a model. In the second part, a heat flux is removed and natural convection cools investigated structure on the both surfaces.

B. Results and Discussion

The evolution in time of temperatures in defective A_d and non-defective A_{nd} areas and absolute thermal contrast C_a is presented in Fig. 5. Initially, there is drastic increase of temperature during heating stage, whereas in the cooling stage, just after reaching maximum absolute temperature contrast C_a at time t_{maxC}, at first there is rapid decline of temperature and then there may be observed stabilization of temperature till the final equilibrium with the environment.

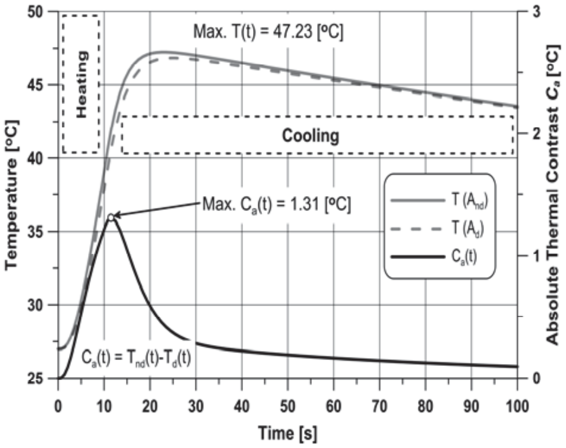

Fig. 5 Numerical results of temperature evolution in defective A_d and non-defective A_{nd} areas and C_a

Abnormal distribution of the temperature on the investigated outer surface of the 3D numerical model of the cylindrical panel is caused by presence of the artificial delamination in the structure. One can observed drop of temperature within defective area - Fig. 6. Maximum contrast C_a can be observed just after the end of heating stage in time t_{maxC} equals to 10.77 s.

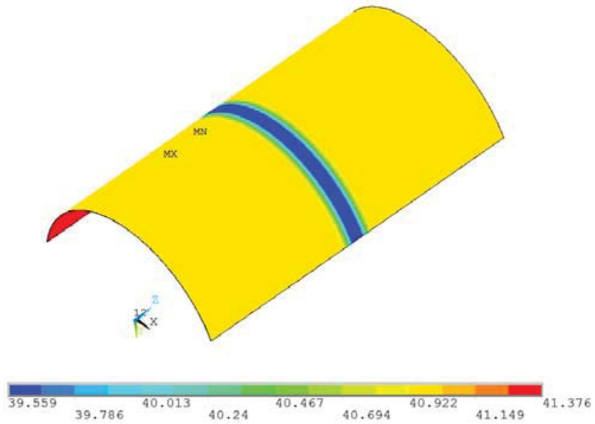

Fig. 6 Temperature distribution on the front surface of investigated 3D numerical model of curved composite panel with circumferential delamination at the time of maximum contrast occurrence (10.77s)

Given the ability of present FE model to account for change in defect thickness, an analysis as to the magnitude of maximum absolute contrast C_a versus thickness of the defect t_d was done - Fig. 7. One can observe that there is quite good correlation between the thicknesses of artificial defects t_d and maximum absolute thermal contrast C_a. It can be also stated, that the thicker defects show a higher C_a which consequently leads to easier and faster detection of such a defect.

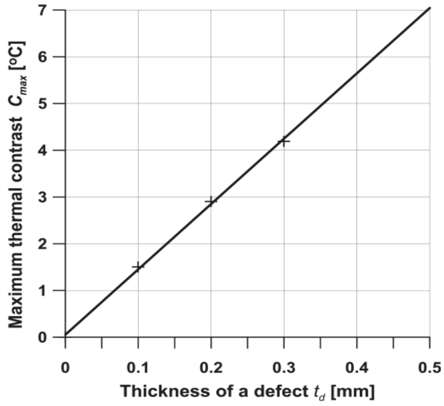

Fig. 7 Maximum absolute thermal contrast C_{max} versus thickness of a defect t_d

IV. Experimental Studies

A. Specimens Description

The specimens were manufactured from 8 plies of Hexcel TVR 380 M12/R-glass unidirectional prepreg layers. The geometry of specimens was cylindrical with a nominal thickness equals to 2 mm, the length 300 mm and the inner radius 92 mm. The laminate had a nominal fibre volume of 60% and the ply thickness equals to 0,25 mm.

To provide compromise between realistic representation and the ease of preparation the delamination, the Teflon film in the form of a single square with the thickness equals to 0,1 [mm] and the width equals to 20 mm was introduced during the manufacturing stage in the middle of the laminate specimens between 4th and 5th layer on the circumference of the sample. Position of these inserts in relation to specimens is identical as in numerical studies and it is presented in Fig. 3.

In order to ensure high quality of the specimens and repeatability of the manufacturing process, all la3minates were cured in the autoclave at 135 °C for 120 min at 4.5 bar of the pressure and 0.8 bar of the partial vacuum. Additionally, to minimize the residual stresses generated during the production and arising from the anisotropy of the thermal expansion of the composite materials, heating and cooling stages were done at 2 °C per minute. This process is schematically illustrated in Fig. 8.

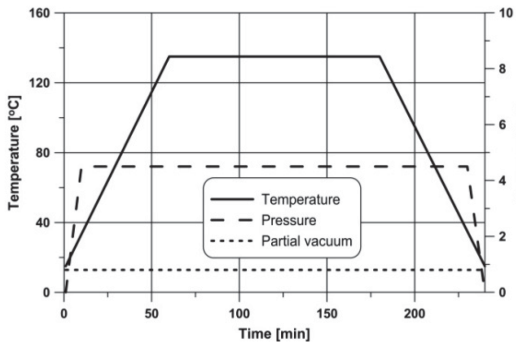

Fig. 8 Diagram of the manufacturing process of the examined specimens

B. Test Station

The modular system used in this study consists of Flir A325 camera with a frame rate of 60 Hz and a focal plane array pixel format of 320x240, the dedicated for curved structures halogen lamp, wattmeter, the computer and the trigger box. All these components are mounted on very stable base that allows the exchange of individual parts depending on the applied procedure. Fig. 9 shows the complete experimental setup used in the current investigation.

Fig. 9 Test station

The entire AIRT measurements was completely controlled by the PC with the use of IR-NDT software. The same program was also used to the acquisition and partial processing and analysing of the data. Additional analysis of thermogram sequences was carried out using more user friendly Researcher Pro ver. 2.10 software. The same program together with the Researcher Pro 2.10 were used to the processing of the acquired data. Furthermore, tests were monitored using a standard camera.

C. Test Procedure

Applied in current investigation procedure of AIRT is based on rapid heating of the surface of a sample by high intensity halogen lamp dedicated especially for curved structures. The temperature is observed both during heating and cooling stages by highly sensitive infrared camera which records series of thermograms at regular intervals in time domain. The thermographic inspection was carried out under the transmission mode, where the IR camera and the thermal stimulation unit were arranged on the opposite sides of the investigated object.

During the analysis of thermal images, all external emitters were eliminated and laboratory was shaded in order to mitigate the environmental disturbances.

D. Results and Discussion

The thermal history was recorded and processed in the form of thermal image sequence. Due to great amount of acquired data, only selected results are presented herein.

From the thermograms, the curves of surface temperature evolution in time within defective A_d and non-defective A_{nd} areas and Absolute Thermal Contrast C_a obtained experimentally was extracted - Fig. 10. It can be seen, that similarly like in FEM results, maximal temperature contrast appears in just after end of heating stage. One may observe that the character of curves and their amplitudes are comparable. It can be stated that numerical results show good correlation with experimental ones. Small discrepancies may be caused by experimentally unidentified thermal properties used in the numerical model and fluctuations of investigated surface emissivity.

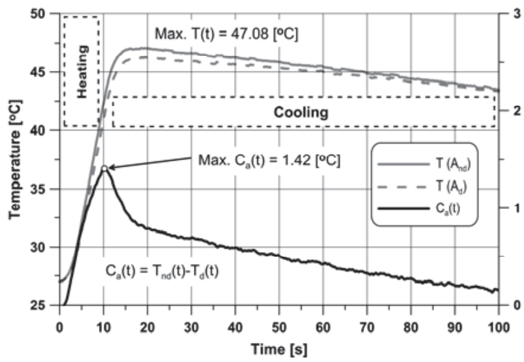

Fig. 10 Experimental results of temperature evolution in defective Ad and non-defective A_{nd} area and Ca

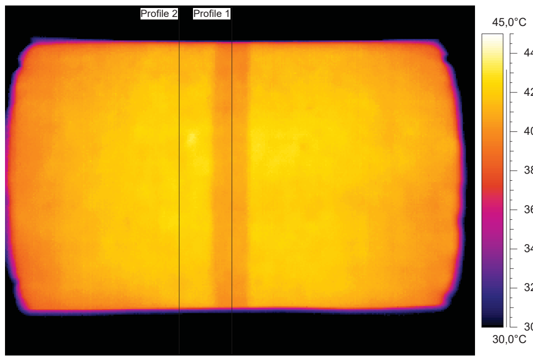

Fig. 11 Example of experimental thermogram of curved composite panel with circumferential delamination

One may observe that circumferential defect can be easily detected – Fig. 11. As can be seen, the artificial defect, namely, embedded during manufacturing stage PTFE insert appeared as cold spot. The temperature around the defects is higher than within the delaminated area, this temperature contrast indicates the presence of a defect and pinpoints its location. It is caused by different thermal properties of composite material and Teflon insert. In essence, owing to these differences, it is possible to reveal subsurface discontinuities. Dedicated halogen lamp was applied in order to obtain homogeneous deposition of radiation on induced curved surface. Despite of this operation, temperature distribution on investigated surfaces are not perfectly uniform comparing to numerical results. It is caused by due to environmental disturbances and influence of noises on recorded signals.

During conducting a research on curved shells, the angular dependence of emissivity which is strongly connected with temperature determination should be taken into account. Circumferential temperature contrast despite its variation caused by noises is acceptable from perpendicular to approximately 60 degrees, then it goes down drastically in contrast to numerical results where these phenomena were not included in the model and it is constant - Fig. 12. It means that defect detection and characterization in practice beyond the safe range of angular contrast can be incorrect, if this factor will not be taken into account and the shape correction of thermal images will not be done.

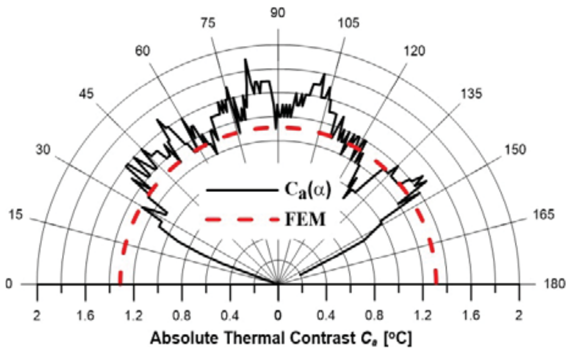

Fig. 12 Polar diagram of the maximum contrast C_a

V. Conclusions

The obtained results proved the effectiveness of used technique and provide further information for active infrared thermography as a viable nondestructive evaluation tool for testing of curved multilayered composite structures. The phenomena observed during the experiments can be successfully simulated by means of the FEM.

Acknowledgment

The research project was funded by the National Science Centre in Poland conferred on the basis of the decision DEC-2013/09/N/ST8/04360.

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