TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
MECHANICS | MECHANIKA
1-M/2016

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AN EVALUATION OF DELAMINATION IN COMPOSITE STRUCTURES BY COOLING DOWN THERMOGRAPHY (CDT): NUMERICAL STUDIES

OCENA DELAMINACJI W STRUKTURACH KOMPOZYTOWYCH Z UŻYCIEM TERMOGRAFII OCHŁADZANIA: BADANIA NUMERYCZNE

Abstract

This paper is devoted to numerical studies of composite structures with delaminations made with the use of CDT. Analysis of temperature distribution provides the opportunity to determine the geometry of subsurface defects. Results confirm the validity of the FE model in comparison to previous experimental investigations.

Keywords: Cooling Down Thermography (CDT), Composite Plates, Delamination, Finite Element Method (FEM)

Streszczenie

Praca jest poświęcona badaniom numerycznym struktur kompozytowym z delaminacjami z wykorzystaniem CDT. Analiza rozkładu temperatury daje możliwość określenia grubości defektów podpowierzchniowych. Wyniki potwierdzają słuszność opracowanego modelu numerycznego w porównaniu do wcześniejszych badań eksperymentalnych.

Słowa kluczowe: termografia ochładzania, płyty kompozytowe, delaminacja, metoda elementów skończonych (MES).

DOI:

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1. Introduction

Nondestructive tests (NDT) are able to provide subsurface defect information without compromising the structural integrity of the examined object. Among the broad variety of NDT techniques is Infrared Thermography (IRT) – this has several unique advantages that distinguishes it from the other techniques: speed of measurement, lack of contact, cost effectiveness, inspection of large flat and/or curved areas. Furthermore, this non-invasive technique creates opportunities to apply it practically in any process where temperature plays a crucial role.

The advancement of IR system technology triggered extensive research in many fields of science. Despite numerous studies, there remains a lot of space for cognisance and the development of IRT methods. In Ref. [1], a new procedure for the thermal/infrared non-destructive testing of composite plates is presented. The authors of this work proposed an application of the thermoelectric module as a source of the heat flux change. The investigated samples were firstly cooled down and they were then exposed to a higher ambient temperature. An infrared camera monitored the surface temperature variation in both the cooling and heating stages in order to reveal subsurface flaws. Nevertheless, the conducted experiments were limited to several specimens due to the high costs of the examined composite structures and time.

The CDT approach creates new possibilities for testing components which cannot be heated due to, for example, thermal expansion or space limitation of the excitation source. In addition, this approach provides a high speed of measurement. It should also be noted that the shown procedure presents some disadvantages in terms of versatility.

Numerical analysis is useful for considering nonlinear phenomena, complex geometries, various boundary conditions, anisotropic materials, etc., without the expense of the manufacturing and testing of many specimens. Analytical solutions are restricted to idealistic scenarios with regard to shapes, selected boundary conditions and isotropic materials that are free of defects – of course, such limitations are impractical for industrial applications. The two most popular numerical approaches in engineering are the Finite Difference Method (FDM) and the Finite Element Method (FEM). The FEM offers capabilities to better understand the 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/or thermal loads.

Numerical modelling and its further comparison to experimental data provides a unique opportunity to study the particular effects on thermal behaviour of the investigated object. Examples where the FEM was successfully applied to simulate classical thermographic tests of multi-layered composites [2, 3] and fibre metal laminates [4] can be found in the literature.

The main aim of this work is to simulate the CDT tests of composite structures with various delaminations and to investigate their impact on thermal response.

2. Active Infrared Thermography

The theoretical aspects of AIRT are well known; therefore, they are not discussed in this work. However, an outline of the most important procedures is presented in order to highlight their novel approach. Broad considerations of the issues presented in this paragraph connected with the fundamentals of AIRT can be found, for example, in Refs. [5-7].

In short, Infrared thermography (IRT) is the field of science that allows visualisation of the emitted infrared radiation in the form of thermal images. Additionally, it includes further signal processing, modelling, computation and analyses of the temperature patterns. Generally, infrared non-destructive testing methods can be divided into active and passive techniques. The difference between them is the origin of the infrared radiation emitted by the investigated surfaces. In the passive thermography, the temperature of the examined object is monitored either during normal operation or immediately after the end of the work – this is in contrast to active techniques which require external stimulation source.

Active infrared thermography is based on the monotonic or periodic supply of external energy to the investigated object. In order to reveal hidden flaws with this type of method, a dynamic temperature field (heating or cooling) is generated. This procedure is caused by equal temperatures of the defective and healthy (non-defective) areas of the examined material during steady state; therefore, it is necessary to excite it. Depending on the form and quantity of supplied energy, AIRT can be divided into the following approaches: pulse thermography (PT), lock-in thermography (LT) and vibrothermography (VT) [8-10].

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

It should be noted that the 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 on a measurement, for example, in many practical cases, the transmission method cannot be applied due to inaccessibility of the back surface. Reflection configuration allows the provision of information about the defect depth but only near the investigated surface – this is in contrast to the two-sided method, which is able to reveal deeper defects [8-10].

3. Thermal contrast

Subsurface flaws may be identified by their temperature signals on the examined surfaces. The basic and most commonly used measure of defects is the temperature difference between the pre-selected reference area, which is assumed to be non-defective, and the defective area. This simplest case in thermal non-destructive testing and evaluation (TNDT&E) nomenclature is called an absolute thermal contrast C_a [6]. The main drawback of this basic measure used for defect detection and quantification is the linear dependence on the amount of absorbed energy during the heating stage. It can be described, for CDT two-sided procedure, as follows:

$$C_a(t) = T_d(t) - T_{nd}(t) \tag{1}$$

where T_d is the temperature of the defective region and T_{nd} is the temperature of the non-defective region of the examined specimen.

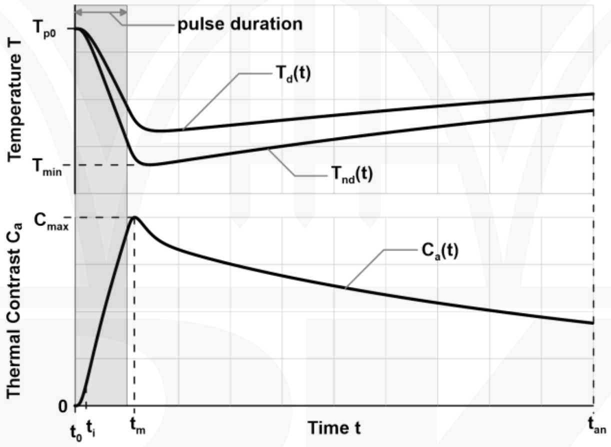

Fig. 1. Temperature and thermal contrast curves with distinction of characteristic points of CDT analysis

The thermal contrast defined in Eq. (1) unfortunately depends strongly on heat flux transmitted through the analysed specimen (assuming uniform one-directional heat flux through the specimen) which in many cases, may be defined incorrectly. Therefore, the dimensionless thermal contrast for the two-sided method of IR-NDT is proposed herein:

$$C_{ar}(t) = \frac{T_d(t) - T_{nd}(t)}{T(t_0) - T_{min}} = \frac{C_a(t)}{T(t_0) - T_{min}} \tag{2}$$

where $T(t_0) = T_{p0}$ is the temperature at the beginning of analysis and T_{min} indicates the minimum temperature of the specimen (in the non-defective area) occurring during analysis (Fig. 1). It is assumed that the difference between the defective and non-defective temperatures at the beginning of analysis ($t = t_0$) is zero.

Values of the defined contrast vary between 0 and 1. A zero value indicates a lack of defect in the analysed specimen $\underset{t}{\forall} T_d(t) = T_{nd}(t)$, and a value of 1 may only occur in time t_m in the case when the temperature of the defective area remains equal to T_{p0} $\underset{t}{\forall} T_d(t) = T(t_0)$. A value 1 indicates infinite heat flux resistance of delamination.

The impact of initial conditions, heat flux and thermal properties on this type of contrast is mitigated which creates an opportunity to compare various thermographic results.

4. Numerical studies

4.1. Description of FE model

In order to predict the thermal behaviour of the investigated object, transient heat transfer analyses were performed for 2D model with various artificial defects. A commercially available ANSYS package version 12.1 was used for this purpose. Implementation of the model was carried out with the use of the ANSYS parametric design language (APDL). This provides the opportunity to automate both simple and complex tasks associated with the creation of areas, meshing, boundary conditions etc. APDL scripting language was also used to retrieve information from the ANSYS database after calculations such as temperature runs and distributions.

Fig. 2 shows the schematic geometry of a composite structure with distinction of the delamination location and boundary conditions. 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} = 25°C was used in the numerical model both as a boundary and as initial conditions. The convective coefficient corresponds to the value recommended in the literature for natural convection in a still air environment (h = 10).

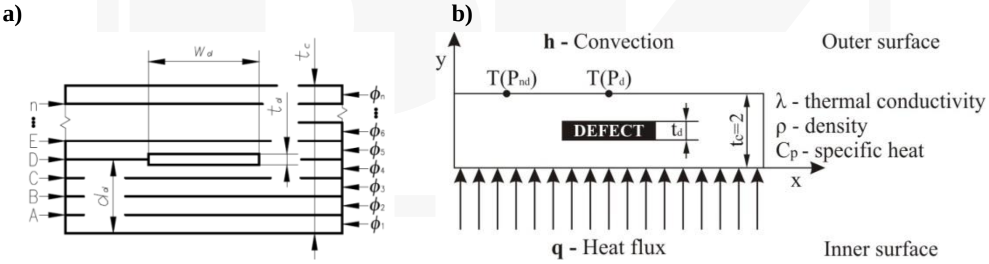

Fig. 2. a) Geometry and location of the delamination, b) boundary conditions

All simulations were carried out in the transmission mode where heat flux was applied on the inner surface and the outer surface was observed during both heating and cooling stages. The entire thermal analysis last for 100 seconds and consisted of two load steps. In the first loadstep, the density of the heat flux was set to -8000W/m^2 in order to simulate negative heat flux such as in the thermoelectric module. It was instantaneously and uniformly imposed on the inner surface and last continuously for 10 seconds while the front surface was being cooled by natural convection. In the second stage, the heat flux was removed and the investigated structure was cooled by natural convection on the both surfaces.

In the present investigation, the PLANE77 element was used – this is a higher order version of the 2D, 4-node thermal element (PLANE55) and it has one degree of freedom (temperature) at each node. It is also worth mentioning that selected to current analysis 8-node elements is well suited to model curved boundaries and mitigate curvature effects. PLANE77 can be applied to a steady-state and/or, what is more important for this work, transient thermal analysis. In this element, orthotropic material directions correspond to the element coordinate directions. Convection or heat flux (but not both) and radiation may be input as surface loads on the element faces. Heat generation rates may be input as element body loads at the nodes. If the model containing this element is also to be analysed structurally, the element can be replaced by an equivalent structural element (such as PLANE183) [13].

Artificial delamination was simulated by the area with different thermal properties. This is justified by similar conditions in experiments [1] where the defect was simulated by PTFE foil in the form of a single square inserted between individual layers of the laminate during the manufacturing stage. In order to accurately represent the thermographic process in the composite structure it is necessary to define the biased mesh around the delamination – this is shown in Fig. 3.

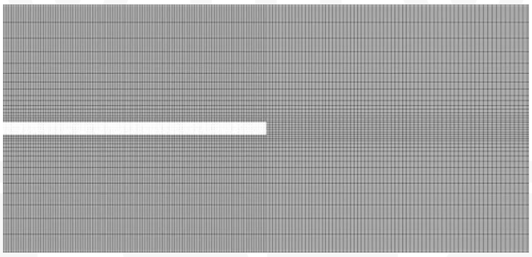

Fig. 3. Magnification of the biased mesh of the delaminated area.

The thermophysical properties of selected materials used during the modelling of CDT are given in Table 1. It should be noted, that these values can considerably differ for other types of laminates or even of the same type composed of identical reinforcement and matrix but performed with the use of a different curing cycle. Therefore, only compatible and experimentally validated data provided by research centers is given herein.

Table 1

Thermophysical properties of selected materials

Material	**Thermal conductivity λ [W/mK]**	**Density ρ [kg/m^3]**	**Specific heat capacity C_p [J/kgK]**	**Reference**
GFRP (∥fibre) along the fibres	0.929	1960	840	[11]
GFRP (⊥fibre) transverse	0.544			
PTFE (Teflon ®)	0.250	2170	1050	[12]

4.2. Results and discussion

After the solution of the posed problem of the thermal response of the composite structure with delamination it is possible to illustrate the computation results. It can take the form of temperature distributions in the model at any moment in time of the analysis, as well as the temporal evolution of the temperature in the chosen points and/or areas. This information is used for further computations of thermal contrasts which are measures of defects. Characteristic points on the contrast evolution curves, such as the time of maximum contrast occurrence t_m and inflection time of the contrast evolution t_i are especially considered.

The presence of the defect alters the heat flow through the laminate resulting in abnormal temperature distribution on both surfaces of the investigated composite structure. This can be observed in Fig. 4.

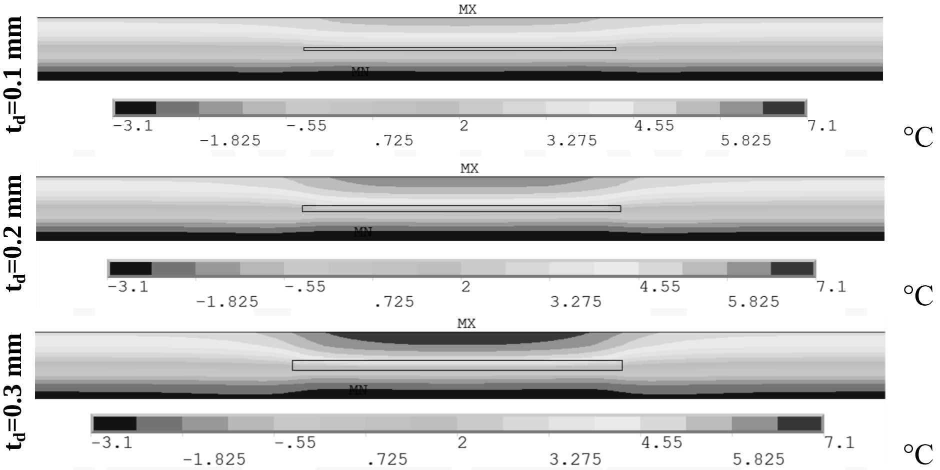

Fig. 4. Temperature distribution through the thickness of the composite structure with various delaminations captured at the time of maximum contrast t_m

In Fig. 5, the temperature profiles on the outer surfaces of the investigated composite structure with various delaminations at the time of maximum contrast t_m are presented. It can be stated that an above average temperature on the outer surface reveals the presence of a resistive defect in the structure. This temperature contrast indicates the presence of a defect and pinpoints its location. It should also be mentioned that a constant temperature in the non-defective area results from neglecting noises from the surroundings and the research equipment.

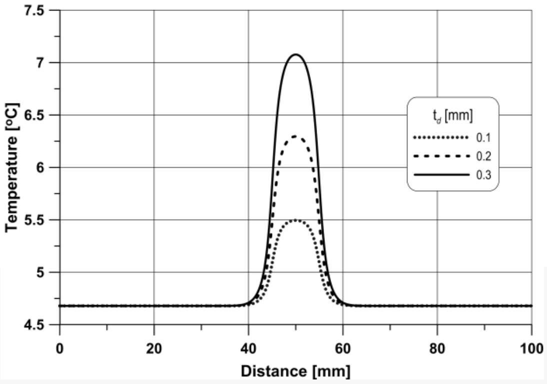

Fig. 5. Temperature profiles on the outer surfaces of the investigated composite structure with various delaminations at the time of maximum contrast t_m

In Fig. 6, the temperature runs within the defective and non-defective areas and thermal contrast evolution C_{ar} for different delamination thicknesses t_d are presented. Initially, there is drastic decrease of temperature during the cooling stage. In the heating stage, after reaching maximum thermal contrast C_{ar} at time t_m, there is a near steady increase of temperature towards the final equilibrium with the environment.

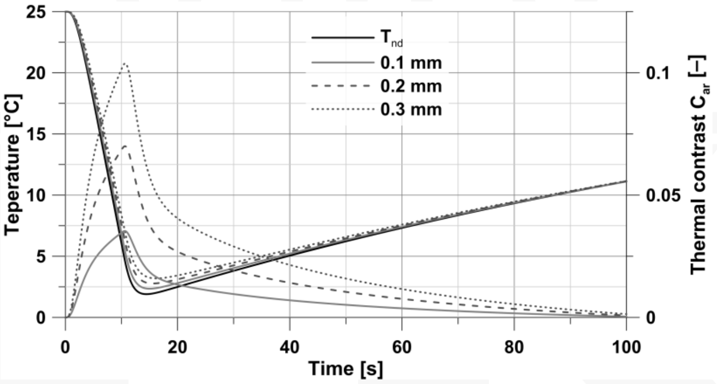

Fig. 6. Temperature runs within defective and non-defective areas and thermal contrast evolution C_{ar} for different delamination thicknesses t_d

Given the ability of the present parametric FE model to account for change in the defect thickness, an analysis of the magnitude of maximum thermal contrast C_{ar} and inflection time t_i versus thickness of the defect t_d was carried out – the results are plotted in Fig. 7. One can observe that in both cases, there is linear correlation between considered variables. It can also be stated that the thicker defects show a higher C_{ar} and t_i which consequently leads to easier and faster detection of such a defect. It should also be noted that the time of maximal contrast occurrence t_m is constant for all thicknesses of the defect (10.6 seconds) and inflection time of the contrast evolution t_i is heat flux independent.

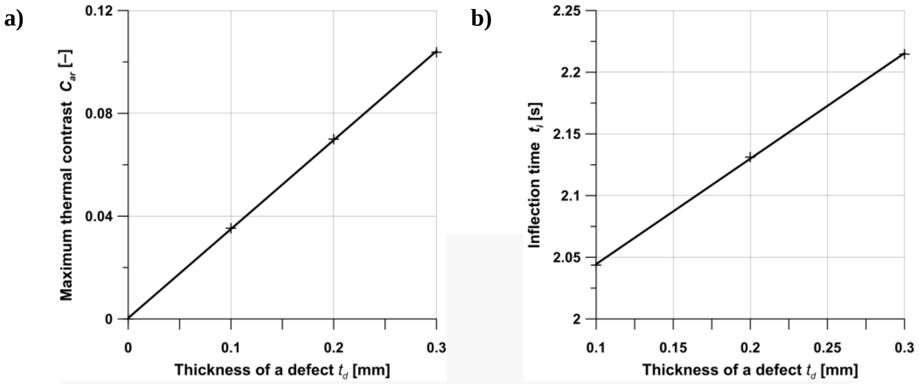

Fig. 7. Maximum thermal contrast C_{ar} and inflection time t_i versus thickness of a defect t_d

5. Conclusions

This paper has shown that CDT can be successfully and effectively simulated by FE numerical modelling. It creates an opportunity to investigate various cases in a short period of time. The thickness of a defect can be determined by the maximum thermal contrast C_{ar} and inflection time t_i which change linearly and are independent from heat flux. Further experimental and numerical studies are needed to investigate other types of defects with various thermal properties.

Acknowledgment

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

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