Title: Detection of delamination in composites using embedded electrical grid and thermovision

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## ABSTRACT

The proposed approach assumes that the structure is equipped with a specially designed electrical circuit of a 3D grid layout, composed of high resistivity elements and embedded in the structure. The special layout of the electrical circuit activated by small currents provides a scattered source of thermal field in the laminate. It is assumed that mechanical properties of the circuit elements exhibit failure which is coincident with the commencement of delamination and its subsequent propagation. These breaks in the electrical network cause changes in the thermal field which will be observed by a long-wave thermovision camera (the temperature range will span a few Celsius degrees above the environment temperature).

A numerical model of layered composite structure with delamination will be presented. The description will be focused on numerical simulations leading to the proper design of the embedded electrical circuit. Experimental verification will be demonstrated for a simple specimen under impact loading.

## INTRODUCTION

Grid systems in SHM may be considered as an alternative to approaches based on wave propagation. General concept of such patent-pending system [1] has been described in [2]. The aim of this paper is to adapt the electrical grid embedded in the structure in such a way that it is able to detect delamination in composites on the basis of observation of temperature field generated by the grid, using a thermovision camera. The proposed approach is believed to be competitive to standard thermovision techniques.

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Thermovision techniques, which are generally used in manufacturing industry for process control, was for long time limited by measurement sensitivity and possibilities of fast (high frequency) data acquisition. As soon as these problems got overcome, thermovision cameras became a valuable and tool for damage diagnostics at quite affordable prices. Experimental thermoelastic analysis of stress state in structures was developed in mid 80s in the form of the SPATE system [3] using sensitive infrared detectors to measure small temperature changes. The advent of thermovision enabled a come-back of this methodology with new sensitivity ranges. Intensification of research based on thermal field observation was a natural consequence. Many researchers started using thermovision techniques for damage detection purposes as well [4]-[10].

The most popular thermovision techniques are:

- Pulsed thermography - where thermal excitation sources work in an impulse mode and measurements are collected during self-cooling phase of the object,
- Lock-in thermography - where thermal excitation is harmonic, and amplitudes and phase shift in relation to the excitation signal are analyzed,
- Step-heating thermography - where excitation sources are laser impulses which interact with object locally (the thermal conductivity is determined in this method on the basis of thermal field rate)
- Vibrothermography - where excitation is mechanical (most often by ultrasound waves) and the object response to this is a thermal wave perturbation coming from the defect

Some of those techniques were used to detect delamination in composites. Despite the fact that delamination zones reveal different thermal behaviour (which can be captured by sensitive thermovision) than the sound composite material, it is still a challenge to detect not very extensive or deep-below-surface zones of delamination. The proposed method is dedicated to detection of delamination in layered composites. The goal is to make the identification possible for small or deeply situated damage zones, with standard thermovision measurement techniques.

The proposed technique uses a specially designed 3D electrical grid embedded in the structure and composed of through-layer and surface layer elements as shown in Fig. 1.

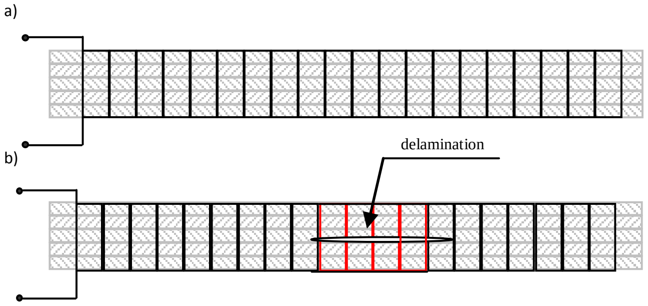

FIGURE 1. Composite structure with embedded electrical grid: a) intact state, b) damage state resulting in a break of electrical circuit

A small current applied to the grid generates a scattered thermal field corresponding to the grid layout. It is assumed that the conductors of the grid have such mechanical properties which neither strengthen nor weaken the composite material.

Further it is assumed that the embedded electrical grid does not interfere in the possible process of delamination of the composite layers. In other words, loss of the adhesion between layers in some area is accompanied by simultaneous break of the grid conductors in this area. Consequently the thermal field density in the delamination zone will be decreased. The effect of forced temperature field will be experimentally observed by a long-wave thermovision camera. The temperature range will be a few degrees above the environment temperature. Thanks to the simultaneous failure of the composite and the embedded electrical circuit, the damaged area will be visible as a low temperature region.

## NUMERICAL MODELLING OF GRID-INDUCED THERMAL FIELD

In this section of the paper some numerical results will be presented. The temperature fields for damaged and undamaged specimen will be compared and resolution issues will be discussed.

The material chosen for modeling is a glass-epoxy composite. Thermal conductivity coefficient values are k=1 W/Km for the glass and k=0.24 W/Km for the epoxy matrix. The glass/epoxy volumetric ratio is 0.45. Rectangular cross-section of the glass fibre was assumed. The size of a fragment of the composite containing one fibre embedded in the matrix is characterized by the following dimensions: $b_2$=0.001 m, $b_3$=0.001 m, $c_2$=0.001 m, $c_3$=0.001 m. Equivalent thermal conductivity coefficients for a single layer are: $k_x$=0.582 W/Km, $k_y$=0.508 W/Km, $k_z$=0.374 W/Km. The modeled sample of composite consists of 6 layers placed symmetrically with respect to the neutral axis ($0/90/0/_{\mathrm{Sym}}$). Equivalent thermal conductivity coefficients for a multi-layer composite are $\underline{k}_x$=0.557 W/Km, $\underline{k}_y$=0.533 W/Km, $\underline{k}_z$=0.374 W/Km.

The following assumptions have been made:

- the diameter of the conducting wire of the grid, perpendicular to the composite layers is small compared to the in-plane distance between the wires
- the in-plane conducting wire of the grid, placed on the outer surfaces of the composite sample is of small resistivity and small cross section so that their temperature should rise significantly less than the temperature of the wire perpendicular to composite layers
- heat is transferred to the environment by convection through the outer surfaces while the boundaries are isolated (this is supposed to model a fragment of a larger composite)

The assumed data is the following: length=4.5 cm (i.e. 90 x 0.05 cm), width=3 cm (i.e. 60 x 0.05 cm), height=0.6 cm, grid's constant=0.3 cm (distance between regularly place wires perpendicular to composite surface), applied temperature=30$^{\mathrm{o}}$C, outer temperature=20$^{\mathrm{o}}$C, convection coefficient $\alpha$=10 W/(m$^2$ $^{\mathrm{o}}$C).

Fig. 2 (a) depicts the thermal picture of the composite equipped with the conducting grid, locally subjected to thermal sources in the places of installation of perpendicular wires. The undamaged state shows regularity of the thermal field corresponding to the layout of the grid. The thermal picture related to the defect is presented in Fig. 2 (b). The delamination zone can be easily identified by a lower temperature area indicating damage. Three delamination zones, schematically sketched in Fig. 2 (c), are considered. Fig. 2 (d) presents cross-sectional variation of temperature in the composite along the line L1 (cf. Fig. 2 (c)). It is clear that the damage extent and temperature drop are positively correlated. It was also observed that the higher the convection coefficient the bigger the temperature drop in the composite due to damage, which can be followed in Fig. 2 (e), (f).

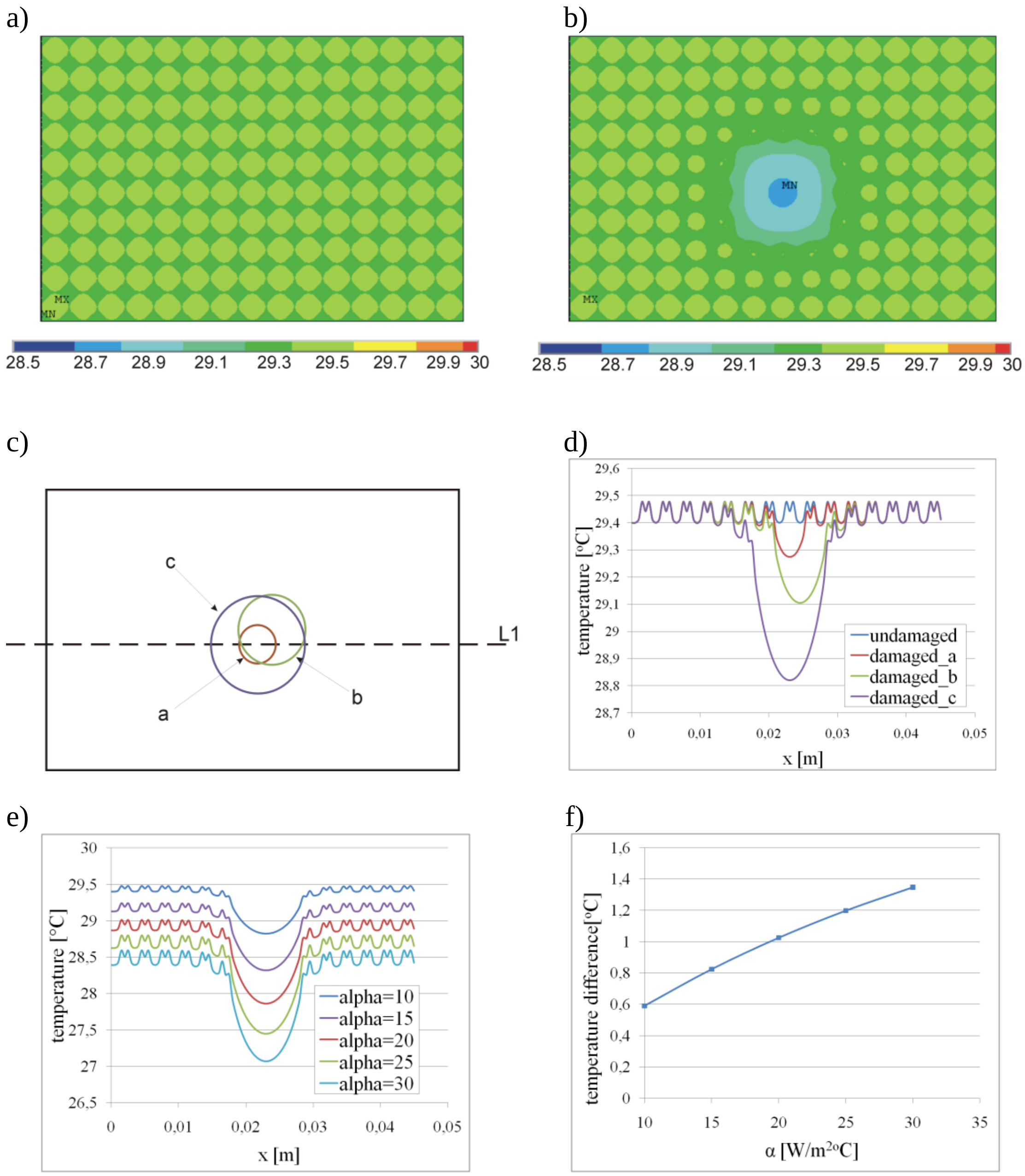

FIGURE 2. Intact composite subjected to thermal sources through the electrical grid (a), delaminated composite subjected to thermal sources through the electrical grid (b), sketch of three zones of delamination considered (c), temperature drop in selected cross-section due to delamination of various extent (d), temperature drop in selected cross-section due to delamination size c for various convection coefficient values (e), temperature difference between healthy and delaminated composite as a function of convection coefficient (f).

## SIMPLE EXPERIMENT

A simple experiment providing a preliminary assessment of the possibility of detecting delamination in composites using thermal excitation and the embedded electrical grid was carried out. The investigated composite consisted of eight layers of a glass mat impregnated with epoxy resin. Small holes were drilled in the specimen in which the conducting wires perpendicular to the composite layers were mounted with the help of epoxy resin.

The composite specimen was subjected to a series of impacts in order to initiate delamintion between the layers. Due to a few impact loads applied, a break of one wire perpendicular to the layers was observed, which was interpreted as emergence of delamination in this area – see Fig. 3 (a-c). Subsequent impact loads caused the delamination zone to expand, which was evidenced by the break of the neighboring wire – see Fig. 3 (d-f). The presented thermal pictures were registered by the thermovision camera at the 0.5 A current applied to the embedded electrical grid.

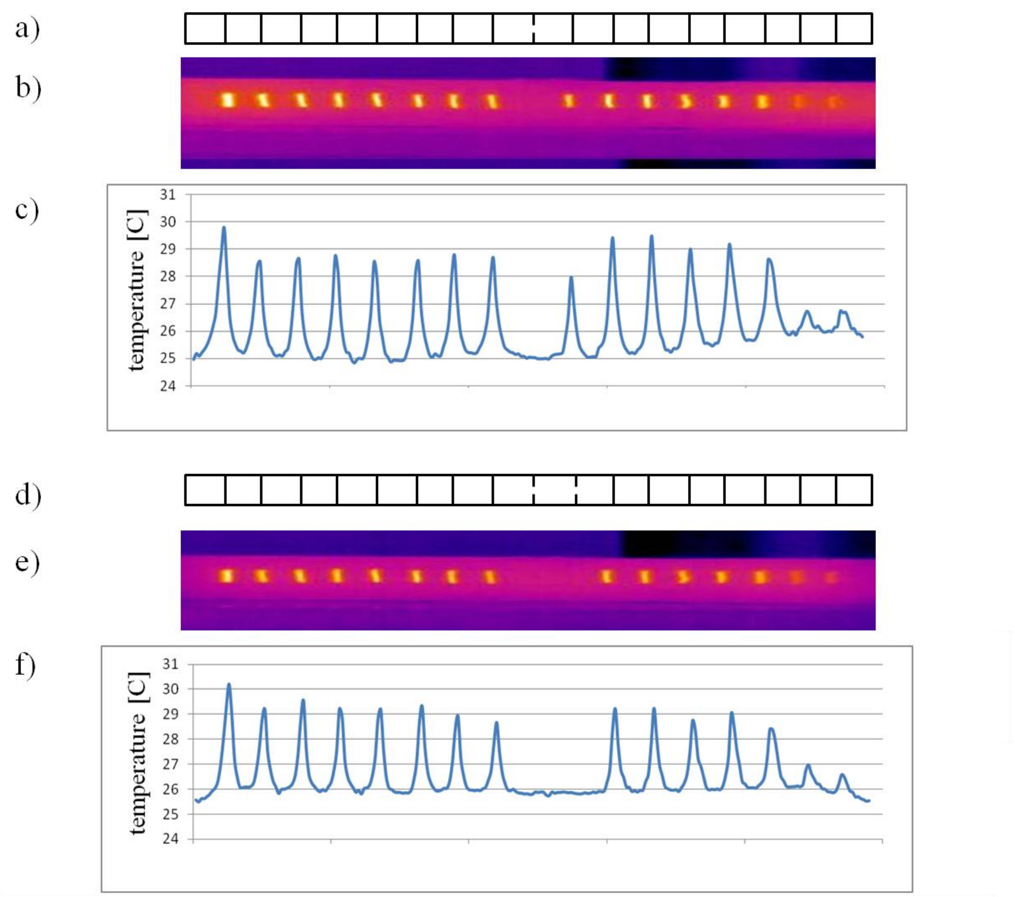

FIGURE 3. Cross section of the composite indicating a break in the electrical grid due to first series of impact loads (a), thermal picture of the outer surface of the composite showing the initial delamination zone (b), temperature profile along the cross section depicted in (a) with an evident temperature drop in the delamination zone (c), cross section of the composite indicating another break in the electrical grid due to second series of impact loads (d), thermal picture of the outer surface of the composite showing the extended delamination zone (e), temperature profile along the cross section depicted in (d) with an evident temperature drop in the delamination zone (f).

## CONCLUSIONS

The presented approach to detection of delamination in composites seems to have a perspective. A thermovision camera of middle-class parameters is quite enough to observe the changes of thermal field due to damage. The essence of the approach is to equip the composite with a specially designed electrical grid, which should facilitate the observation of damage. This grid plays the role of exciter of the investigated composite, which is usually done by high-power lamps or infra-red radiation devices when the thermovision technique is used. The proposed approach is quite straightforward in interpretation. It can also be applied to thick composites, in which delamination might occur deep under the outer surface.

Further research will be concentrated on the proper choice of conducting materials for the electrical grid embedded in the composite. The properties of the wires perpendicular to the composite layers and the in-plane wires should be different. Special attention will be paid to the perpendicular wires as they ought not to influence the mechanics of the composite itself.

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