AN INVESTIGATION ON THE ELECTRICAL RESPONSE OF DELAMINATED LAMINATES

M. Zappalorto, F. Panozzo, P.A. Carraro, M. Quaresimin

Department of Management and Engineering, University of Padova,
Stradella San Nicola, 3, Vicenza, 36100 (VI), Italy
Email: michele.zappalorto@unipd.it

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ABSTRACT

In the present work, experimental tests are carried out to investigate the possibility of monitoring the presence of delamination through electrical measurements in composite parts. Then, an analytical model is presented, capable of correlate the length of the delamination and the electric potential distribution of the part. The model is applied to predict the electrical resistance change of a Double Cantilever Beam (DCB) specimen, as a function of its delamination length. DCB tests are carried out on conductive specimens made of carbon fibre/cyanate-ester resin, with a simultaneous measurement of the delamination length and of the DC electrical resistance. Experimental tests confirm that the growth of the delamination results in an irreversible increase of the electrical resistance. Analytical predictions, compared with the experimental results, show a satisfactory agreement.

1 INTRODUCTION

The demand for reliable methods for structural health monitoring of composite parts has dramatically grown in the last few decades, as well as the associated efforts in the development and optimization of techniques for the real-time assessment of the damage state in composite parts. In fact, structural applications may lead to the presence of damage in the material. In addition, composite parts may be subjected to impacts, causing a localized damage such as cracks and delaminations between the plies. As a consequence, the overall reliability and safety of a component could be compromised, with a reduction of the stiffness and the load bearing capability. In most of the cases, the internal damage may be barely detectable by visual inspection. Therefore, tools for the health monitoring of composite structures are highly desirable in many applications. Among the several techniques available for this purpose, electrical methods received a particular attention in the last decade.

In the field of monitoring the presence and the extent of a delamination, some contributions can be found in the literature [1-5]. Despite some efforts in the development of analytical models to correlate the variation of the electric properties of the material to the delamination length, at present most of the works are mainly experimental. An analytical model would be highly desirable, both for the possibility of predicting the electrical resistance change of a damage component, as well as to design the material to have the best sensitivity possible.

In the present work, an analytical model is presented to calculate the electric potential distribution of a conductive composite plate in the presence of a delamination between the central plies. An analytical procedure is given to calculate the electric resistance of the laminate, and its variation as a function of the delamination length. Then, electrical resistance of conductive DCB specimens, made of carbon fibre/cyanate ester resin, was measured during Mode I DCB tests. An irreversible increase of the electrical resistance was measured as a consequence of the delamination growth. The predictions of the analytical model, compared with the experimental results showed a very satisfactory agreement.

2 ANALYTICAL MODELLING

Consider a composite plate made of electrically conductive plies. A duty current, I, is injected through the lateral surfaces, as represented schematically in Figure 1. Each ply is supposed to have an orthotropic behaviour in terms of electrical properties, with a longitudinal resistivity η_x, and a through-the-thickness resistivity η_z.

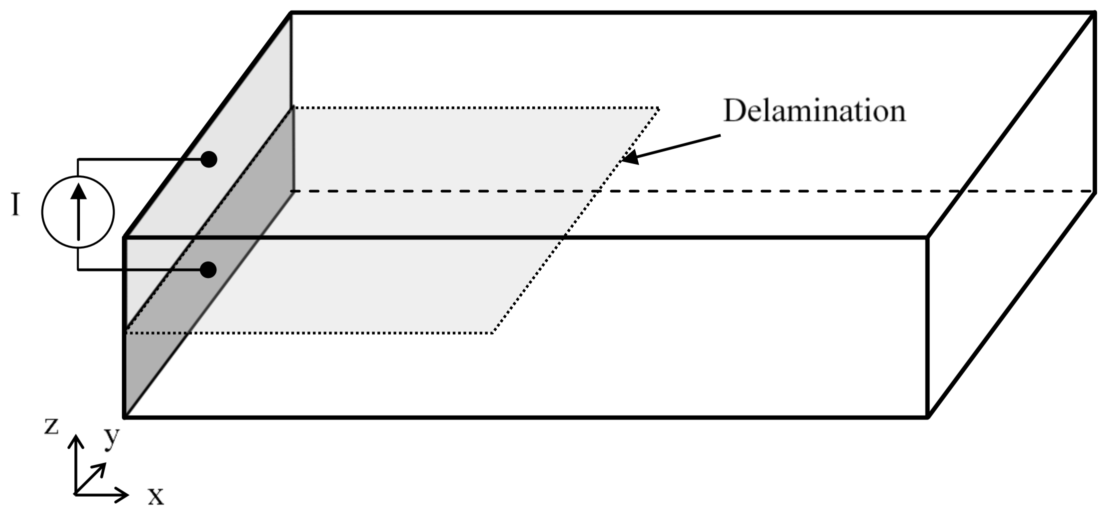

Figure 1: Schematic representation of the laminate with the presence of a delamination.

As schematized in Figure 1, the laminate presents a delamination between the central plies. The following hypotheses are made:

- the delamination is of the same width of the laminate;
- the delamination represents a geometrical interruption, so that no current can flow between the two delaminated faces.

According to these hypotheses, the problem can be treated as plane, since the current flowing along the y-direction is equal to zero. With reference to Figure 2, the laminate has been subdivided into two different zones:

1) Delaminated zone (number 1 and 3 in Figure 2);
2) Non-delaminated zone (number 2 in Figure 2).

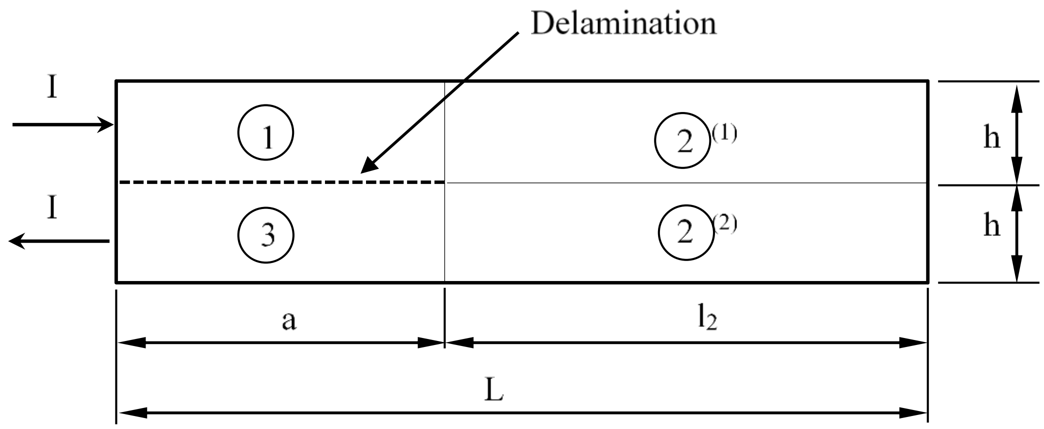

Figure 2: 2D representation of the laminate.

According to this schematic, and assuming a unitary width of the laminate, it is possible to treat zones denoted with number 1 and 3 as Ohmic resistors, the electrical resistance given by:

$$\Delta V_1 = \Delta V_3 = \eta_x \; I \; \frac{l_1}{h} \tag{1}$$

Differently, in the non-delaminated zones, the z-component of the current density is different from zero. As a consequence, electric potential depends on the z-coordinate. As proposed in Ref [6], starting from an initial hypothesis of a parabolic trend of the electric potential along the z-coordinate, the expression of the potential difference between zone $2^{(1)}$ and zone $2^{(2)}$ can be expressed as:

$$\Delta V_2 = \frac{2}{\sqrt{3}} \sqrt{\eta_x \cdot \eta_z}\ I\ coth\left[\frac{1}{h} \sqrt{3 \frac{\eta_x}{\eta_z}} (L-a) \right] \tag{2}$$

Eqs. (1-2) can be combined to calculate the potential drop of the entire laminate [6]:

$$R = \frac{\Delta V_1 + \Delta V_2 + \Delta V_3}{I} = 2\eta_x \left[\frac{a}{h} + \frac{1}{\sqrt{3}} \sqrt{\frac{\eta_z}{\eta_x}}\ coth\left[\frac{1}{h} \sqrt{3 \frac{\eta_x}{\eta_z}} (L-a) \right] \right] \tag{3}$$

Eventually, for an initial delamination length a_0, the ratio between the increase of the electrical resistance and its initial value is given by [6]:

$$\frac{\Delta R}{R_0} = \frac{R(a) - R(a_0)}{R(a_0)} = \frac{a - a_0}{a_0 + \frac{h}{\sqrt{3}} \sqrt{\frac{\eta_z}{\eta_x}}} \tag{4}$$

As expected, Eq. (4) states that the electrical resistance of the specimen increases as the delamination length is increased, thus confirming that electrical methods are suitable to monitor the extent of the delamination. Moreover, Eq. (4) indicates that a higher sensitivity is expected for laminates with a low η_z/η_x ratio, encouraging the nanomodification of the composite with conductive nanoparticles to increase the through-the-thickness conductivity.

However, due to the multiple simplification adopted, predictions of Eq. (4) may result inaccurate especially for higher values of the thickness of the laminate, and for high η_z/η_x ratios. In Ref [6], a refined solution is provided to overcome these limitations, based on the subdivision of the laminate in a number of sub-layers, each one characterized by a parabolic trend of the through-the-thickness electric potential trend. The charge conservation is applied for all the sub-layers, turning out in a system of second order differential equations to be solved in the unknown current densities in the longitudinal direction. The boundary conditions require that no current has to flow across the faces of the delamination [6].

3 EXPERIMENTAL

DCB tests were carried out on specimens made of carbon fibre/ cyanate ester resin. A plate made of unidirectional plies, with the dimensions of 300x250 mm^2 was supplied by Adamant Composites Ltd. (Greece). The laminate was composed by 18 pre-preg layers of T700s carbon fibers, with a final layup of $[0]_{18}$. A Teflon layer was interposed between the middle plies during the lamination process to create a pre-crack. The plate was cured in an autoclave for 2h at 180 °C and eventually post-cured for 2h at 230°C.

From the manufactured panel, rectangular specimens were cut with size 230mm x 25mm x 2.95 mm thick, as represented in Figure 3. Specimens presented an initial delamination length of 90 mm, and load was applied through hinges bonded to the specimens.

Electrical resistivity measurements were carried out by means of a dual channel sourcemeter Keithley 2604B (Keithley Instruments, Usa). Silver painted electrodes were placed on the specimens according to the schematic shown in Figure 4. Three DCB tests were performed in displacement control, with a crosshead speed of 2 mm/min. To measure the delamination length during the tests, a traveling optical microscope with a 40x magnification was adopted.

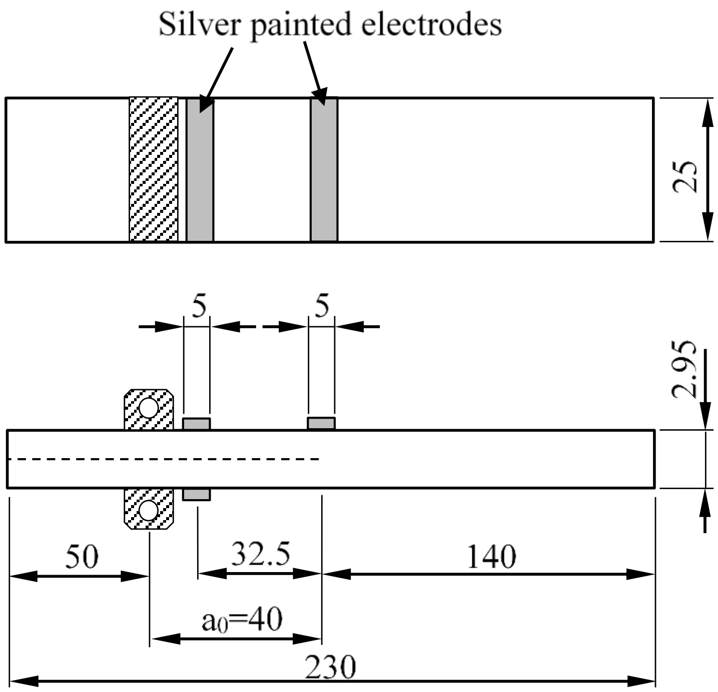

Figure 3: Dimensions of the specimens.

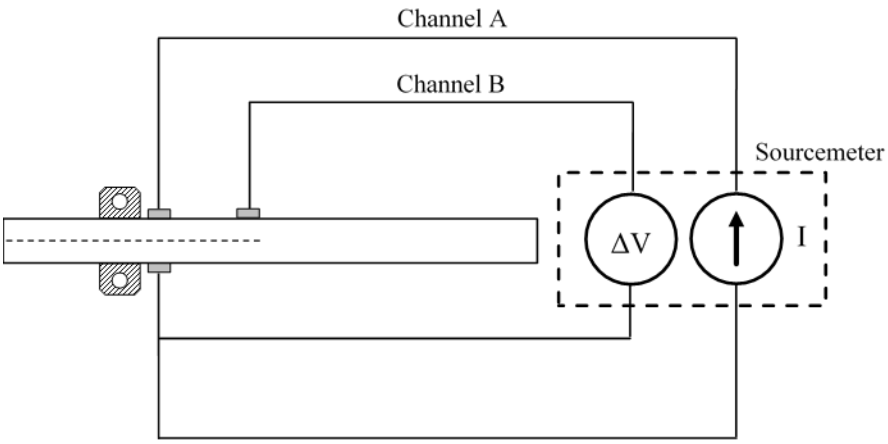

Figure 4: Electrical scheme for DCB specimens.

The specimens were continuously observed during the loading ramps. When the propagation of the delamination was detected by the operator, the specimen was unloaded down to a 1 mm displacement. Then this condition was hold for 20 seconds and the specimen was loaded again until a new propagation was observed. The electric potential difference between the electrodes of channel B was measured during the entire test and it was seen to sensibly increase as the delamination propagated, as shown in Figure 5.

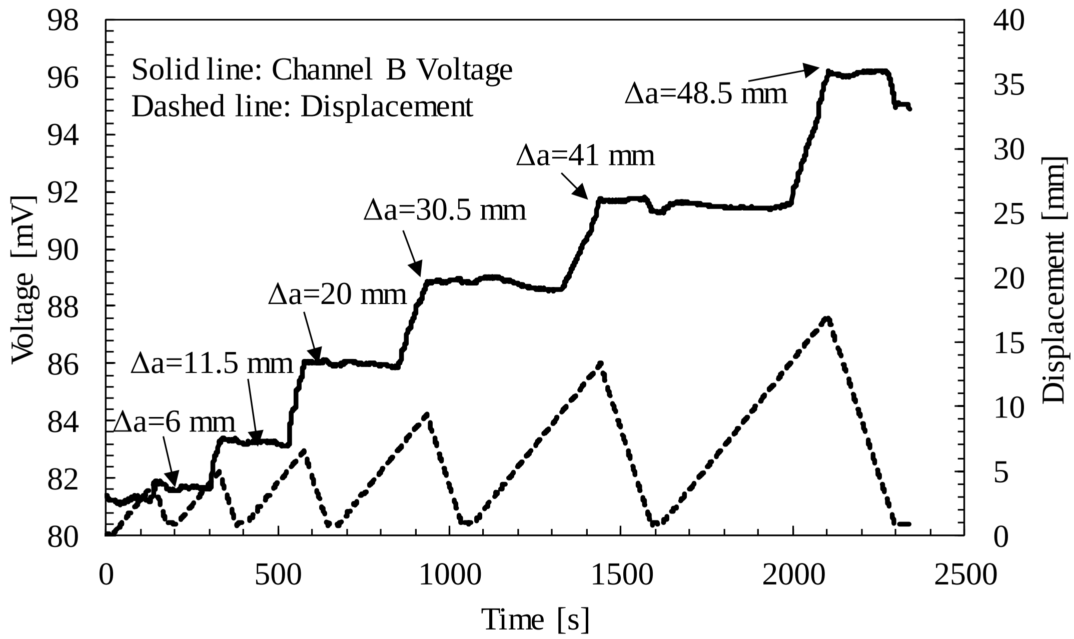

Figure 5: Experimental results of a DCB test.

4 MODEL VALIDATION

In Figure 6, the results of the combined mechanical/electrical test are shown. The increment of the channel B (see Figure 4) electrical resistance, ΔR, normalized by its initial value, R_0, is plotted as a function of the delamination extension, a-a_0. Electrical resistance increases of 30% for a delamination Δa of 60 mm, proving the delamination sensing capability of the electrical method. In addition, a comparison between the analytical prediction of the refined model, and the results of the experimental campaign is shown in Figure 6, where an overall good agreement is evident.

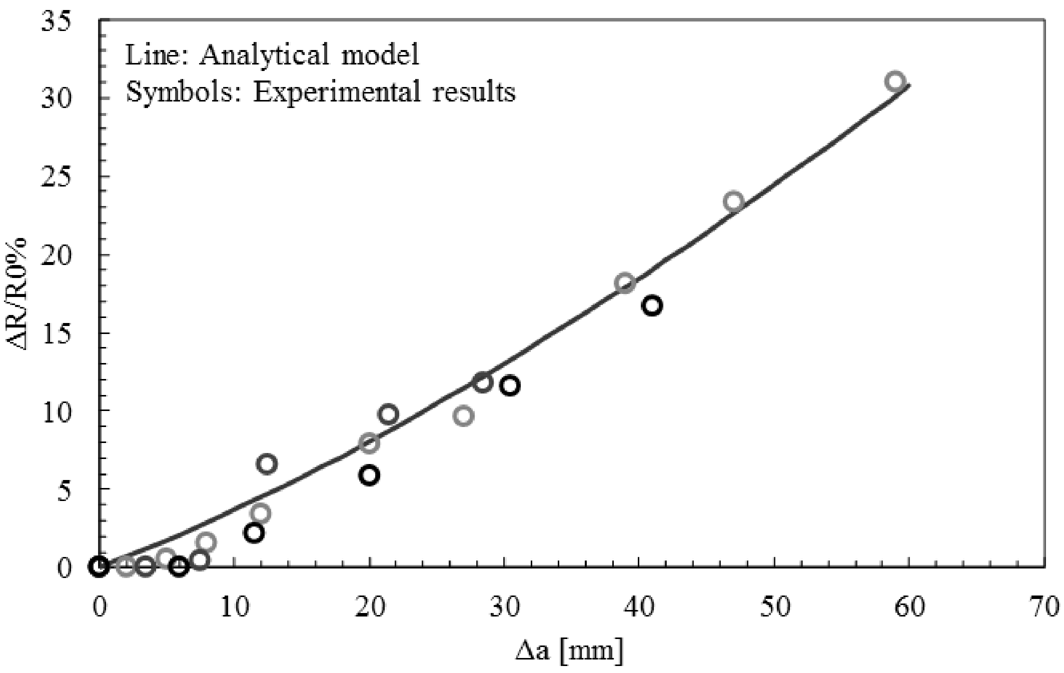

Figure 6: Comparison between the experimental results and the analytical predictions.

5 CONCLUSION

In this work, an analytical study is carried out to assess the electrical response of conductive laminates with the presence of a delamination between the central plies. Initially, a theoretical model is developed, presenting an analytical expression to correlate the length of the delamination and the increase of the electrical resistance of the part. Then, an experimental campaign is carried out on unidirectional specimens made of conductive carbon fibre/cyanate-ester resin. The specimens, manufactured with a pre-crack, were subjected to a Mode I opening load, measuring at the same time the delamination length and the corresponding electrical resistance.

A comparison between the analytical predictions and the experimental results showed a very good agreement, confirming the capability of the model to predict the presence and the extent of the delamination.

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