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# Electrical response of a laminate with a delamination: modelling and experiments

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An analytical and experimental study is carried out on the electrical response of a laminate with a delamination. The present study represents a basis for the detection of delaminations in conductive laminates through electrical measurements. As an example of application, the case of a Double Cantilever Beam (DCB) specimen is considered, with the aim to calculate the electric potential of a point on the surface of the laminate, and its variation as a function of the delamination length, highlighting the most influencing parameters.

The accuracy of the theoretical predictions is verified against a number of finite element analyses, showing an extremely satisfactory agreement. In addition to this, theoretical predictions are also validated by comparison with a bulk of experimental data coming from an ad-hoc campaign, as well as using data taken from the literature. In all cases a good agreement is found.



## 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. Indeed, due to the high stiffness and strength of Fibre Reinforced Polymers (FRPs), combined with their low density, manufacturing of key structural components made of composite materials has become a solid alternative to conventional steels and aluminum alloys, with an increased use especially in the transportation, wind turbine and aerospace industries [1]. During their in service life, composite parts may be subjected to fatigue loads and impacts, causing a localized damage such as cracks and delaminations between the plies, as experimentally documented by several authors [2–4]. 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 might be barely detectable by visual inspection. Therefore, tools for the health monitoring of composite structures are highly desirable in many applications.

Within this context, many solutions have been investigated to monitor the delamination extension in composite parts. Among these, worth of mentioning are Fibre Bragg Grating (FBG) sensors, wave-based and electric potential-based methods. FBGs have been used within Double Cantilever Beam (DCB) specimens to monitor the delamination growth during Mode I tests [5], and within cross-ply laminates made of CFRP to detect delaminations induced by low-velocity impacts [6]. A relationship between the damage size and the variation of the FBG spectrum was shown to exist. However, the FBG technique presents some limitations, such as the costs associated to the implementation of a dense network of sensors, as well as the cost of the interrogator unit. In addition, embedding optical fibres within the material could be detrimental for the fatigue strength of the part. The damage in composite parts has been monitored also taking advantage of wave-based methods. Wang et al. monitored the delamination onset and growth under Mode I and Mode II loadings using guided waves, sent through the material and received by piezoelectric actuators and sensors [7]. Toyama and Takatsubo used Lamb waves to inspect impact-induced delaminations in composite laminates [8], showing that it was possible to quantitatively evaluate the size and the location of the damage. Despite the use of wave-based methods is capable of monitoring the damage and degradation of the material, several sensors are needed for large structures, and an overall low resolution of the method represents an issue to be overcome.

Methods based on the electrical conductivity of carbon fibres

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have also been widely investigated in the literature. Their effectiveness in monitoring the stiffness reduction due to fatigue loads [9,10] and, more generally, the damage accumulation [11,12] has been successfully proven. The location and the extent of delaminations caused by impact tests on CFRP laminates were estimated by Angelidis and Irving [13], through the measurement of the DC electric potential. Abry et al. [14] used the electrical resistance change as a quantitative parameter to monitor the damage state in unidirectional CFRP specimens under buckling bending tests, identifying the failure of the fibres as the cause of the electrical resistance increase. Fischer and Arendts [15] developed an electrical method to determine the delamination length on the basis of the electrical resistivity change of DCB specimens, which proved to be very accurate if compared with optical measurements. Similar results were also found by other authors [16–18], who observed a monotonically increasing trend in the electrical resistance with the delamination length. Schulte et al. [19] showed that a propagating crack in a MWCNT/epoxy compact tension specimen is associated to an increase of the electrical resistance.

However, so far, the topic of delamination detection by electrical measurements has been thoroughly studied by the experimental point of view, whereas only few works can be found in the literature dealing with modelling activities. Ueda et al. [20], as well as other authors [21,22] used an approximated statistical method to estimate the delamination size from the measured electrical resistance change of CFRP laminates. Differently, Todoroki [23,24] developed an analytical model based on the analogy between the current density within a plate and the flow of a perfect fluid without vortices to obtain an analytical expression of the electrical current density valid for strongly orthotropic infinite plates. Such a model was later extended to thin cross-ply laminates made of CFRP with the presence of a delamination [25].

A successful engineering application of electrical methods for health monitoring of composite parts requires models capable to soundly predict the damage state on the basis of resistance measurements. In order to succeed in this ambitious aim, in the authors' opinion, great efforts have still to be done in terms of modelling activities, in order to better understand the most important material and geometrical parameters influencing the phenomenon and to effectively quantify their effects. In particular, the availability of a model correlating the damage extension to the electrical measurements in the components would assist, by one hand, an effective health monitoring of composites parts. On the other hand, it can be useful to design the best material solution for a specific application.

As a first step in this direction, in the present work, an analytical, numerical and experimental study is carried out on the electrical response of a conductive laminate with a delamination.

Initially, a fully analytical model, is proposed to assess the electrical resistance increase in a laminate due to the presence of a delamination. Such a model has the advantage to be extremely simple to be used and, especially, to make explicit the role played by the most important material and geometrical parameters, such as the resistivity of the plies and the laminate thickness. However, even if providing important qualitative information, it is not accurate enough for thick laminates and it can be only applied to unidirectional laminates with orthotropic plies.

In order to overcome these limitations, a more accurate and comprehensive model is later proposed to calculate the electric potential distribution on symmetric composite laminates made of electrically orthotropic plies, based on a ply refinement procedure.

As an example of application, the case of a Mode I inter-laminar fracture toughness test (DCB) is proposed, calculating the electric potential of a point on the surface of the laminate, and its variation as a function of the delamination length. Theoretical predictions are compared with a bulk of finite element analyses, as well as with experimental data, showing in all cases a very satisfactory accuracy.

## 2. A simple model to evaluate the variation of the electrical resistance of a delaminated plate

Consider a composite plate in the presence of a delamination in the mid-plane, as schematically represented in Fig. 1a, where a constant current I is injected on the side surfaces. The material of which the laminate is made of is supposed to have an orthotropic behaviour in terms of electrical resistivity. In particular, with reference to the global coordinate system shown in Fig. 1a, the plate is characterized by the in-plane and the out-of-plane resistivities $\eta_x$ and $\eta_z$, respectively.

These hypotheses allow the problem to be treated as a two-dimensional one, since the y-component of the current is identically equal to zero in the whole laminate. Accordingly, the analysis can be restricted to the geometry shown in Fig. 1b, where the plate has been divided into four different zones:

- Delaminated zones of length a (identified with numbers 1 and 3 in Fig. 1b);
- Non-delaminated zones (numbers $2^{(1)}$ and $2^{(2)}$ in Fig. 1b).

The voltage differences of the entire laminate among the current injection faces can be calculated as the sum of two different contributions:

- A potential difference in the x-direction in the zones 1 and 3;
- A potential difference in the z-direction at the delamination front in zone 2.

According to this schematic, the current in the delaminated zones is oriented only along the x-direction, so that the delaminated zones can be treated as ohmic resistors, characterized by a resistivity $\eta_x$. The voltage differences of zone 1 and 3, for a laminate with a unitary width, read as:

$$\Delta V_1 = \Delta V_3 = \eta_x I \frac{a}{h} \quad (1)$$

In the non-delaminated zones, the presence of the delamination causes the perturbation of the current density and the

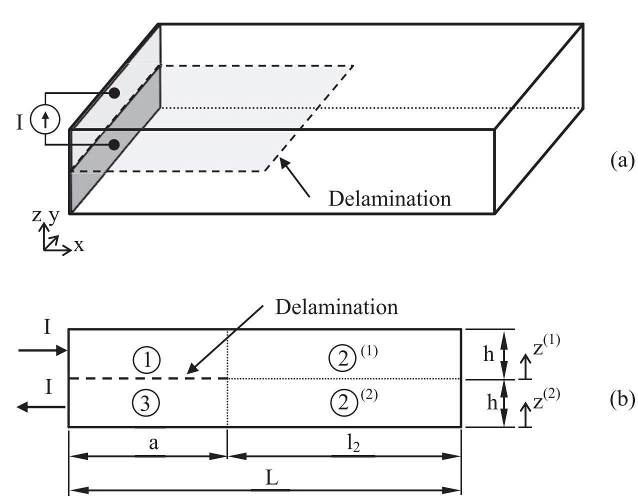


**Fig. 1.** (a) Schematic of a laminate characterized by the presence of a delamination between the central plies. (b) 2-D representation of the delaminated plate.