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Estimation of residual stresses in laminated composites using field measurements on a cracked sample

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ABSTRACT

Today, advanced damage models taking into account residual stresses are available. In particular, microcracking as a degradation mechanism in laminates is very sensitive to manufacturing-induced stresses. However, these stresses are often introduced through a model parameter whose identification remains difficult or requires time-consuming and costly additional tests. Here, we propose a relatively simple method based on the observation of the displacement field associated with the creation of a transverse crack in a crosswise laminate. Subsequently, this displacement field can be reinterpreted according to the model being used in order to build the quantity required by the model.

1. Introduction

Because of their manufacturing process, laminated composites are subject to residual stresses which can be significant and lead to various consequences between the manufacturing stage and the end of the application's life [1]. These residual stresses can have different sources: thermomechanical sources (different expansion coefficients for the reinforcement and the matrix), chemical sources (matrix shrinkage during polymerization)...(a review can be found in [2]).

A well-known consequence of these initial residual stresses is the problem of the dimensional stability of molded pieces [3]. As far as mechanical degradation models are concerned, these stresses were long ignored, but today most approaches take them into account in behavior prediction. A classical example, which is reported here, is transverse cracking, a degradation mechanism which is well-documented in the literature (see [4,5] for reviews). Several authors pinpointed the need to take into account the residual stresses associated with the manufacturing process in estimating the fracture criterion [6–8]. However, even when the models do manage to integrate these residual stresses, these parameters often remain difficult to identify and evaluate precisely.

A first approach to the resolution of this problem consists in simulating the process as exhaustively as possible in order to deduce these residual stresses from the simulation [9,10]. This is probably the best solution for the long-term future. Today, however, the number of parameters and physical phenomena involved is too large for the whole evaluation to be controlled. A second solution consists in evaluating these residual stresses within the structure. Thus, a series of destructive or non-destructive experimental approaches was gradually derived for this purpose [11]. A classical estimation technique consists in observing the effects of these residual stresses on a geometric modification of the structure. Among other works along these lines, one could mention, for example, studies on bimetallic strips [12] or applications of what is known as the "incremental hole" method [13–17]. Each of these tests must be carried out carefully and represents an additional experiment in the series needed to identify a material.

Here, we propose a simple approach in order to obtain a first approximation of the residual stress state within a ply's material in the context of a study of transverse microcracking. The method consists in observing (using a numerical camera) then analyzing the displacement field generated by the opening of a transverse crack. The multicracking test is classically used in micromechanics to observe crack density/load ratios in order to identify the associated material model [18–20]. During such a test, each occurrence of a transverse crack results in a localized perturbation of the energy density in its vicinity.

The displacement field associated with this perturbation can be calculated through the resolution of a residual problem which can take seemingly different, but actually very similar, forms depending on the authors [4,21,22]. Under linear elasticity assumptions, this perturbation is proportional to the residual field which existed along the crack's lip prior to its occurrence. Therefore, by observing this field one can gain some information about the internal stress state of the composite material [23].

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In the first section, we review the reference problem, which is about the occurrence of a transverse crack in an initially crack-free crosswise laminate. Through a classical decomposition by superposition, we pinpoint the respective roles of the mechanical loading and the initial residual loading in each component of the field. We also emphasize in the related appendix some properties of the residual field thus introduced.

The second section describes the measurement method itself. The objective is to measure the displacements caused by initial residual stresses. The construction of these displacements requires the comparison of two fields, one obtained experimentally through image analysis, the other obtained numerically through finite element simulation. The experimental method for the construction of the first field is described in details and illustrated in the case of a carbon/epoxy laminate with $[0/90]_s$ lay-up.

In the third section, these residual displacements are interpreted in terms of residual stresses and used to measure the "equivalent polymerization temperature" referred to by several microcracking models [24]. The value obtained is fully consistent with the usually accepted orders of magnitude.

2. The reference problem

Let us consider the general case of a cracked cross-ply laminate under generalized plane strains. A more detailed description of the problem is given in Appendix A. Here, we are considering only the two states (cracked and uncracked) of the laminate described in Fig. 1.

By simple superposition, the field of the displacement jump $\Delta\underline{\mathbf{U}}$ between State A and State B is the result of the combination of the external mechanical loading and the internal residual stresses. Let us simply write:

$$\Delta\underline{\mathbf{U}} = \lambda\overline{\underline{\mathbf{A}}}\overline{F} + \underline{\mathbf{U}}^R \tag{1}$$

where $\overline{F}$ is the external loading, $\lambda\overline{\underline{\mathbf{A}}}$ a linear operator (see Appendix A) and $\underline{\mathbf{U}}^R$ the part of the displacement field associated with the relaxation of the residual stresses over the crack's lips. Here, the objective is to evaluate the residual field $\underline{\mathbf{U}}^R$ to obtain the residual stresses; therefore, we simply transform this equation into:

$$\underline{\mathbf{U}}^R = \Delta\underline{\mathbf{U}} - \lambda\overline{\underline{\mathbf{A}}}\overline{F} \tag{2}$$

Eq. 2 involves the mechanical loading (Part $[\lambda\overline{\underline{\mathbf{A}}}\overline{F}]$), the observed displacement fields (Part $[\Delta\underline{\mathbf{U}}]$) and the displacements associated with the residual stresses (Part $[\underline{\mathbf{U}}^R]$). Thus, we are going to use this relation to recover the field $\underline{\mathbf{U}}^R$ associated with the initial residual stresses.

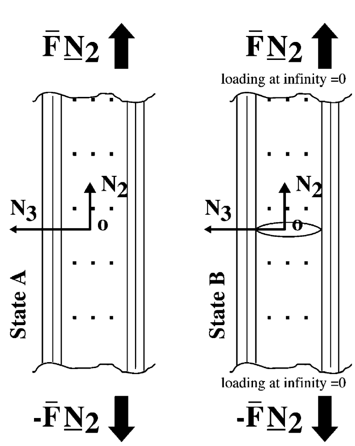

Fig. 1. Cross-ply laminate in traction (A being the healthy state, B the cracked state).

3. Estimation of the residual displacement $\underline{\mathbf{U}}^R$

Thus, the construction of the residual displacement field $\underline{\mathbf{U}}^R$ from Eq. 2 requires/an experimental field: $\Delta\underline{\mathbf{U}}$/and a numerical field: $\lambda\overline{\underline{\mathbf{A}}}\overline{F}$.

Here, we will illustrate the method in the case of a crosswise laminate consisting of a $[0/90]_s$ lay-up of width b = 20 mm. The elementary ply has a width of 0.142 mm and its material characteristics are given in Table 1.

The material is an IM7/977-2 carbon-epoxy provided by EADS, which was in charge of optimizing the polymerization cycle for a supersonic application (a completely stable polymerized material free from post-baking effects). In order to achieve a minimal residual polymerization rate, a post-baking cycle was added to the customary cycle used for this material in subsonic applications. The cycle chosen consisted of a 3-h gelation phase at 150 °C followed by a 2-h polymerization phase at 180 °C. Cooling and heating were applied at a rate of 2 °C/mn. A pressure of 7 bars was applied from the beginning of the cycle until the return to ambient temperature. Post-baking consisted of heating at a rate of 3 °C/mn until 210 °C, followed by 2 h at constant 210 °C temperature, then cooling at a rate of 3 °C/mn until the return to ambient temperature.

3.1. Measurement of field $\Delta\underline{\mathbf{U}}$

This measurement was carried out based on an observation of the sample area using a numerical camera. A numerical camera mounted on a long-distance QUESTAR microscope (Fig. 2) enabled us to acquire data on the edge of the sample.

The macroscopic loading was incremented in ΔF steps. For each load level ($F_n = n\Delta F$), a series of pictures was taken through automatic scanning of the sample area (this step was required because the position of the future crack was of course unknown). The procedure was repeated for each increment. When a transverse crack was detected, the load level was reduced down to the previously recorded level. Then, a picture of the cracked zone was taken in order to play the role of Picture B.

Thus, we had pictures of the zone before and after cracking (Fig. 3) corresponding to the same load level ($F_A = F_B = F$). The size of both pictures was 1024 $*$ 1280px^2. The resolution was 1.66 pixel/micron.

Next, the field of the displacement vectors $\Delta\underline{\mathbf{U}}^{A\to B}$ between the two pictures A and B was obtained by image analysis. The classical technique [25,26] consists in dividing the zone of interest of Picture A (hereafter denoted S_{Obs}) into elementary patterns following a regular grid (Fig. 4). Then, each elementary zone of Picture A is sought in Picture B by correlation, leading to the displacement of the center of the elementary pattern. Thus, the displacement field $\Delta\underline{\mathbf{U}}^{A\to B}$ is obtained in discrete manner at the center of each of the elementary zones. In our case, this operation was carried out using the code CORRELIQ2, which uses a more elaborate version of this technique in which the relative displacements are interpolated through a finite-element approximation [27]. This is illustrated in Fig. 5[b], which shows $\Delta\mathbf{U}_2^{A\to B}$ (the displacement field according to $\underline{N}_2$ between the two pictures) expressed in pixels in the $[Q;\underline{N}_2,\underline{N}_3]$ coordinate system.

This is the raw information issued from the analysis. In order to obtain usable information, two additional operations were carried out on the measured field:

Table 1
Elastic properties of the carbon-epoxy material being used

E_{ll} (MPa)	E_{tt} (MPa)	ν_{lt}	ν_{tt}	G_{lt} (MPa)
157,000	8500	0.29	0.4	5000