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Presentation of a methodology for delamination detection within laminated structures

D. Coutellier [a,*], J.C. Walrick [b], P. Geoffroy [c]

[a] LAMIH UMR CNRS 8530, 59313 Valenciennes Cedex 9, France
[b] E.S.T.A.C.A. 34, Rue Victor Hugo, 92300 Levallois-Perret, France
[c] ONERA – DMSE 5, Boulevard Paul-Painlevé, 59045 Lille Cedex, France

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Abstract

A methodology aiming at taking into account delaminated composite structures behaviour has been developed. This study falls into two parts:

- The first one tackles the delamination detection within damaged thin laminated structures. In the finite element method (FEM) computational code, those laminated structures have been modelled using multi-layered shell elements. The methodology uses post-process criteria, based on fracture mechanics linked with damage mechanics, of computational code by the effective stress tensor.
- In the second place, the influence of delamination over the overall behaviour of the structure is taken into account. This influence is introduced by locally changing material characterization, quite progressively during the loading phase. These integrated effects change the numerical behaviour on loading and energy curves.

The validation is carried out with experimental low velocity impact tests on the bending tests. A satisfactory coherence is shown for damage mechanisms and delamination shapes, in different examples. The methodology developed is recognized a predictive process for several laminates under study. It can be used as a potential tool to size laminated structures at design stage.

We will present the different aspects of this delamination approach.

Keywords: C. Delamination; Composite

1. Introduction

Laminated composites are widely used in numerous fields, more particularly in transportation structures design. In order to comply with safety standards, dimensioning those structures requires to take into account damage phenomena likely to occur during some static or dynamic loading procedures. The laminated materials being submitted to impacts display some sensitivity to delamination, which is detrimental to the structure mechanical integrity [1]. Delamination (i.e. cracks at the interface of differently orientated plies) is combined with ply inter-laminar damage, thus representing a major phenomenon within the laminated material deterioration characteristics, and therefore the damage resulting from a low velocity impact (lower than 10 m/s, less than 100 J) may be hard to detect. This type of damage is detrimental to a satisfactory structure working process.

The main objective of the study carried out consists in allowing to locate and allow for delamination during low velocity impact simulation on a laminated structure

* Corresponding author.
E-mail address: daniel.coutellier@univ-valenciennes.fr (D. Coutellier).

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modelled by means of multi-layer shell type elements. The computations are achieved through FEM using explicit formulae allowing a rapid dynamic study.

The study carried out falls into two phases:

- The first one is based on the implementation of a numerical methodology able to detect delamination initiation and propagation. This approach relies on the joint use of various quadratic criteria widely used in fracture mechanics.
- The second phase consists in integrating the delamination induced damage effects into a computational code. It concerns the overall effects which manifest themselves by an influence over the stress and structure absorbed energy curves.

2. Numerical methodology

The development of a numerical methodology allowing delamination detection within a layer comprehensive shell element [2] is the major originality of this study. The integration of all the constituent plies within a single element is not sufficient to provide a "physical" representation of the inter-laminar crack opening (Mode I of the failure) in the model but quite sufficient to take into account the delamination due to in plane shear and transverse loading.

The first step consists in introducing a thin layer featuring the characteristics of the resin used between the delamination sensitive composite plies (Fig. 1(a)). This thin layer as compared to the associated plies is defined as a rich resin interface allowing the use of delamination detection criteria (fracture is broached through different notions, namely):

An isotropic assumption on the interface thin layer allows the use of a Von Mises approach based on strain energy dw relating to an elementary volume dv,

$$\mathrm{d}w = \frac{1}{2}\sum_i \sum_j \sigma_{ij}\varepsilon_{ij}\,\mathrm{d}v, \tag{1}$$

where σ_{ij} and ε_{ij} are, respectively, stress and strain tensor components.

Thanks to the isotropic relationship between stress and strain, the energy density dw/dv for the interface is given as follow [3],

$$\frac{\mathrm{d}W}{\mathrm{d}v} = \frac{1+v}{6E}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right] + \frac{1-2v}{6E}(\sigma_1+\sigma_2+\sigma_3)^2. \tag{2}$$

Here, σ_i are the principal stress components in the interface, E is the Young's modulus and v the Poisson's ratio.

For the composite plies, a quadratic Tsai-Hill type criterion [4] may be applied for different layers stress tensor. It can be formulated as follows:

$$f^2 = \frac{\sigma_1^2}{X^2}+\frac{\sigma_2^2}{Y^2}-\frac{\sigma_1\sigma_2}{X^2}+\frac{\tau_{12}^2}{U^2}+\frac{\tau_{23}^2}{S^2}+\frac{\tau_{31}^2}{S^2}, \tag{3}$$

where stress components are taken into consideration for the orthotropic ply frame (1 or fibre direction, 2 and 3 for transversal in and out plane).

X is the longitudinal fibre strength, Y the transverse resin strength and U, S failure shear strengths. As for the value of f, it is in-between 0 (no damage whatsoever) and 1 (complete ply fracture). In this methodology, this criterion is applied to composite plies as well as to the interface.

Direct observations of damage growth in multi-layers during loading (Fig. 1(b)), showed that interface delamination being closely connected with adjacent plies damage. So, Tsai-Hill criterion is applied in order to identify the plies fracture modes.

In the FEM explicit code used, an available damage-elasticity model is defined for each composite ply which is modeled as Uni-directional with homogeneous data (with no distinction whatsoever of the mechanical characteristics of the fibre–matrix constituents) [2,5]. This model distinguishes damage modes like fibre fracture, matrix transverse fracture, fibre/matrix debonding (Fig. 2).

Failure in the composite ply is introduced thanks to two variables d and d' whose values can grow from 0 (no damage) to 1 (total failure).

d' is linked to transverse crack in the matrix under tension, and is applied to transverse Young's modulus E_{22} by:

$$E_{22} = E_{22}^0(1-d'),\quad \text{si } \sigma_{22} > 0,$$
$$E_{22} = E_{22}^0,\quad \text{si } \sigma_{22} < 0.$$

With E_{22}^0 initial modulus for the undamaged ply.

d controls the shear cracks in the fibre/matrix interface with the G_{12} shear modulus,

$$G_{12} = G_{12}^0(1-d).$$

With G_{12}^0 representing initial shear modulus for the undamaged ply.

Fibre fracture is given by the critical fracture strain of fibre ε_{11r}.

In this model, rising damage, which is given by d and d', intrinsically depends on internal strain energy within the ply. This notion of stored energy in the element is taken for the delamination model.

So, the methodology developed hereby consists in pairing Tsai-Hill criterion for the plies and defining a new criterion for the interface based on the energy density defined above. The damage ply model described acts directly on criteria as stress values are sensitive to damage growth (d and d') via mechanical modulus evolution.

To define a criterion with the energy density, an experimental static tensile test campaign is carried out. To define composite tensile samples, some stacking se-