Delamination analysis by damage mechanics : Some applications

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INTRODUCTION

The proposed approach concerns the application of damage mechanics for the prediction of delamination of carbon-epoxy laminates. Because of their interactions [1], degradations of the layers and of the connection between the layers are introduced. Both onset of delamination and its propagation on a short distance are predicted.

Simulations of delamination have been compared with experimental results. We present two simulations : (i) delamination in the vicinity of a straight edge of a specimen under tension or compression, (ii) delamination near the hole of a perforated plate under tension.

LAMINATE MODELLING

Damage mechanics of composite laminates is the modelling of progressive degradation phenomena on a structural analysis scale. At this level, the laminate is modelled as a stacking of homogeneous layers connected by interfaces. The interface is a zero thickness medium. The layer modelling has been achieved with Aérospatiale company for T300-914 and IM6-914 laminates.

The elementary layer [2]

Let us note 1,2 and 3 respectively the fibre direction, the transverse direction and the normal to the laminate direction. The principal features of the modelling are :

- The layer behaviour is homogeneous and orthotropic.
- In the fibre direction, the behaviour is elastic and brittle under traction and it is non-linear elastic and brittle under compression.
- The only moduli modified by progressive degradations (matrix micro-cracking and fibre-matrix debonding) are the transverse and shear moduli E_2 and G_{12}. The other independent elastic characteristics remain constant. This is confirmed by experimental observations.
- There is no damage under transverse compression.
- To describe anelastic phenomena coupled with damage a plasticity-like model is used.
- In order to get a damage modelling in agreement with the classical fracture mechanics a meso-modelling of damage is used i.e. the damage variables are uniform in the ply thickness. In add delay damage modelling is introduced.

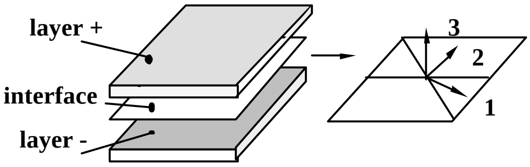
The strain energy under plane stress assumption is :

$$E_D = \frac{1}{2}\left[\frac{<\sigma_{11}>_+^2}{E_1^0} + \frac{<-\sigma_{11}>_+^2}{E10}\right) - \left(\frac{\nu_{12}^2}{E_1^0} + \frac{\nu_{21}^2}{E_2^0}\right)\sigma_{11}\sigma_{22} + \frac{<\sigma_{22}>_+^2}{(1-d')E_2^0} + \frac{<-\sigma_{22}>_+^2}{E_2^0} + \frac{\sigma_{12}^2}{(1-d)G_{12}^0}\left.\vphantom{\frac{1}{2}}\right]$$

$< >_+$ denotes the positive part, the upper script ^{0} is relative to the initial moduli. d and d' are two scalar damage variables.

The interface

The interface ensures displacement and traction transfer between plies. It is assumed to be elastic with damage. An interface with damage has also been used recently by Schellekens [3] for delamination simulation. The interface modelling we propose has been presented in [4].



1 and 2 are the bisectors of the adjacent fibre directions and 3 is the direction perpendicular to the laminate. The strain energy is :

$$E_D = \frac{1}{2}\left(\frac{<-\sigma_{33}>_+^2}{k_3^0} + \frac{<\sigma_{33}>_+^2}{k_3^0(1-d_3)} + \frac{\sigma_{31}^2}{k_1^0(1-d_1)} + \frac{\sigma_{32}^2}{k_2^0(1-d_2)}\right)$$

k_1^0 , k_2^0 and k_3^0 are elastic characteristics of the interface. The variables Y_{di} are associated to d_i :

$$Y_{d1} = \frac{\frac{1}{2}\sigma_{31}^2}{k_1^0\,(1-d_1)^2} \;;\; Y_{d2} = \frac{\frac{1}{2}\sigma_{32}^2}{k_2^0\,(1-d_2)^2} \;;\; Y_{d3} = \frac{\frac{1}{2}<\sigma_{33}>_+^2}{k_3^0(1-d_3)^2}$$

Damage evolution is assumed to be governed by :

$$\underline{Y} = \sup_{\wedge\tau=t}\left(Y_{d3} + \gamma_1\, Y_{d1} + \gamma_2\, Y_{d2}\right)$$

γ_1, γ_2 coupling factors. The damage evolution law is :

$$\begin{cases} d_3 = w(\underline{Y}) \text{if } d_3<1 & d_3=1 \text{ otherwise} \\ d_1 = \gamma_1 w(\underline{Y}) \text{if } d_1<1 \text{ and } d_3<1 & d_1=1 \text{ otherwise} \\ d_2 = \gamma_2 w(\underline{Y}) \text{if } d_2<1 \text{ and } d_3<1 & d_2=1 \text{ otherwise} \end{cases}$$

$$\text{with } w(\underline{Y}) = \frac{<\underline{Y}^n - Y_0^n>_+}{(Y_c^n - Y_0^n)} \quad \text{and} \begin{cases} Y_0 \text{ (threshold energy)} \\ Y_c \text{ (critical energy)} \\ n \end{cases}$$

characteristic parameters of the damage evolution law of the interface.

A first identification of characteristic parameters can be carried out by use of inter-laminar fracture toughnesses of classical fracture mechanics tests [4] [5] [6]. Nevertheless, the study of the onset of delamination is necessary for a complete identification.

SIMULATIONS OF DELAMINATION

Because delamination phenomena are localised, the delamination analysis is carried out as a post-processor of an elastic laminate shell computation. The problem to solve is set into a zone limited to the vicinity of the structure edge.

(i) Near a straight edge [5]

Numerical simulations are given in the framework of the study of delamination onset near the free edge of a specimen under tension or compression. The edge being straight, the problem to solve is a non-linear problem set into a band perpendicular to the edge.

The simulations are compared with experimental results [6] [7] for mode I delamination (on the mid-plane interface) of a T300-5208 material. Then, we also compared our results with experimental ones [8] for mixed mode of delamination of a T300-1034C.

Mode I delamination

Laminate	ε_{exp}	ε_{cal}
$(\pm 45,0,90)s$	0.53	0.53
$(\pm 45_2,0_2,90_2)s$	0.45	0.38
$(\pm 45_3,0_3,90_3)s$	0.36	0.32
$(0,\pm 45,90)s$	0.66	0.61
$(45,0,-45,90)s$	0.54	0.57
$(\pm 30,90)s$	0.39	0.43
$(\pm 30_2,90_2)s$	0.36	0.39

Mixed mode delamination

Laminate	interface	ε_{exp}	ε_{cal}
$(\pm 45,90,0)s$	90,0	0.71	0.77
$(90_4,\pm 30_4)s$	30,-30	-0.27	-0.28
$(90_4,\pm 15_4)s$	15,-15	-0.34	-0.36
$(0_4,\pm 30_4)s$	30,-30	-0.35	-0.4
$(0_2,\pm 15_2)s$	15,-15	-0.51	-0.6
$(0_4,\pm 15_4)s$	15,-15	-0.35	-0.45
$(0_4,\pm 15_4)s$	15,-15	0.57	0.5

(ii) Near the hole of a perforated plate [9]

The problem to solve is non-linear and three-dimensional. We present the analysis of delamination of a $(0_2,\pm 45_2,90_2)s$ T300-914 laminate under tension along the 0° direction. Simulation results are compared with experimental ones from Aérospatiale [10]. This example is very interesting because the onset of delamination does not lead to the specimen rupture which allows to follow the delamination evolution.

Above picture shows the damaged zones just before the rupture (X radiography). Delamination appeared on the (0,-45) and (-45,45) interfaces. A diffused damage is also seen that is interpreted through the simulation as a matrix micro-cracking in the 90, 45 and -45 plies. For the experimental level of rupture, the simulation predicts the fibre breaking in the 0° layer.

Following pictures show the delaminated areas that are simulated on the (0,-45) and (-45,45) interfaces. Dark zones correspond to a total delamination (d_3=1).

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