FINITE ELEMENT DAMAGE PREDICTION OF COMPOSITE STRUCTURES

L. Gornet

Laboratoire Mécanique et Matériaux, Division Mécanique des Structures, Ecole Centrale Nantes, 1 rue de la noë,BP 91101, 44321 Nantes cedex 03, France

SUMMARY: This study recalls the basic principles of a general damage computational approach for laminates and shows its possibilities for simulating the complete fracture phenomenon in the case of complex structures. For composites, continuum damage mechanics models are recalled. They are constitutive relations which, when included in a structural analysis code, are able to predict the damage state at any time and at any point of the studied structure until final fracture. The predictions are obtained with an extended version of the Finite Element code Castem 2000 (C.E.A.) developed specifically for laminate composite structures. This study describes, for carbon-fiber/epoxy-resin laminated composites, some examples of damage and delamination predictions by means of a damage mechanics computational approach.

KEYWORDS: Damage Mechanics, Finite Element Predictions, Delamination .

INTRODUCTION

The aim of this paper is to present examples of damages and delamination predictions by means of a damage mechanics computational approach. Three-dimensional non-linear Finite Element (FE) analyses are conducted for standard delamination tests. Damage refers to the more or less gradual development of microvoids and microcracks which lead to macrocracks and then to fracture. Brittle and progressive damage mechanisms are both present. To simulate the complete fracture phenomenon, a mesomodelling of the material is recalled. This is a semi-discrete damage mechanics approach where the material is described on an intermediate and preferential scale known as the meso-scale. The use of classical damage modelling for the simulation of failure has led to many theoretical and numerical difficulties which are well understood at the present time. With the concept of meso-model, where the state of damage is uniform in each meso-consistuent, main of these difficulties are overcome. This type of modelling, which has a strong physical significance, is not a continuous mechanical one but a semi-discrete one and particular lengths are introduced: the thickness of a single layer for example. In order to obtain a complete consistent computational damage approach, damage model with delay effects has been used. For this model, a variation of the stresses does not lead to an instantaneous variation of the damage variable which is physically correct. There is a certain delay defined by the characteristic time included in the model. In quasi-static problems, the use of such damage evolution laws implicitly introduces a length scale into the governing equations of the problem and then avoids the pathological mesh sensitivity for composite structures. Even though the purpose of this work is quite general, this application concerns the M55J/M18 carbon-fiber/epoxy-resin material which a high

modulus carbon-fiber/epoxy-resin material. Examples of comparisons between prediction and experimental results are provided.

GENERAL TOOLS AND CONCEPTS

Damage concept

The main idea is originally due to Kachanov [1] and Rabotnov [2]: the deterioration of a material can be described by its effects on the elastic coefficients. The classical theory of isotropic damage developed in particular by Lemaitre [3] for metallic is not sufficient to study composite materials. A general approach which is useful in describing damage mechanisms, associated forces and constitutive laws, has been proposed by Ladeveze [4] [5] [6]. Applications to different material composites are given in [7] [8]. Other approachs for composites are proposed by Talreja [9], Allen et al [10]. At the present time, continuum damage mechanics approaches are numerous. The predictions are obtained with an extended version of the Finite Element code Castem 2000 (C.E.A.) [11] developed specifically for laminate composite structures. This code include the damage mesomodel based on two constituents: the elementary layer and the interface. The code is able to compute at any time and at any point, the "intensity" of the different damage mechanisms occurring in the different layers and interfaces. Examples of delamination predictions are shown in [12].

Meso-modeling-concept

For laminates, three different scales can easily be defined: the micro-scale of the individual fiber, the meso-scale associated with the thickness of the elementary ply, and the macro-scale which is the structural one. Due to the low thickness of the elementary ply and the kinematics of the deterioration inside the ply (fiber-oriented), it is possible and worthwhile to derive a material model at the meso-scale. The one proposed in [6] is defined by two meso-constituents: a single layer, and an interface which is a mechanical surface connecting two adjacent layers and dependent on the relative orientation of their fibers (see Fig. 1).

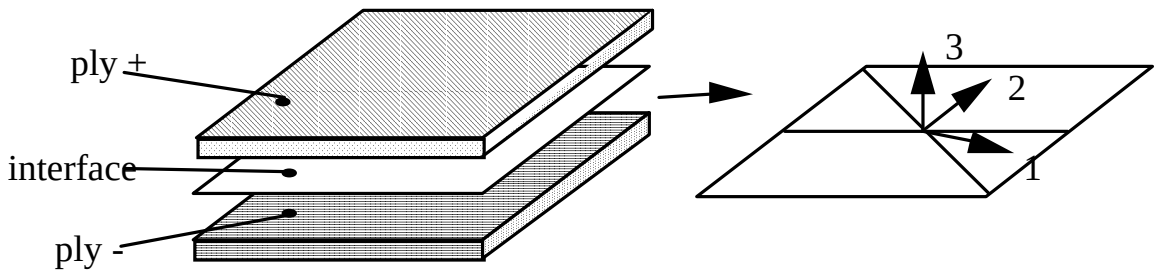

Fig. 1: Laminate modeling and Orthotropic directions of the interface

A meso-model is then defined by adding another property: a uniform damage state is prescribed throughout the thickness of the elementary ply. This point plays a major role when trying to simulate a crack with a damage model. With this property, Damage Mechanics integrate Fracture Mechanics, i. e. it yields a correct value of the critical energy release rate. Let us recall that in order to be able to perform complete analyses of three-dimensional delamination process cases, damage models with delay effects are introduced for the in-plane direction of both the layer and interface. One limitation of the proposed meso-model is that the fracture of the material is described by means of only two types of macrocracks,

delamination cracks within the interfaces and orthogonal cracks to the laminate with each cracked layer being completely cracked in its thickness. Let us recall that the single-layer model and its identification, including damage such as fiber-breaking and transverse micro-cracking, as well as inelastic effects were previously developed in [6][8].

Interface modeling

The interface model is detailed next. The interlaminar connection is being modeled as a two-dimensional entity that ensures stress and displacement transfers from one ply to another(see Fig. 1). This model was previously developed in [13], and F.E. examples of delamination predictions are shown in [12]. The notions and framework that govern the interface damage model are similar to those which are used to derive the layer damage model [6][8]. The effect of the deterioration of the interlaminar connection on its mechanical behavior is taken into account by means of internal damage variables. The different types of damageable behavior in "tension" and in "compression" are distinguished by splitting the strain energy into "tension-energy" and "compression-energy". More precisely, we use the following expression, proposed in [6] for the energy per unit area :

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

Thus three internal damage indicators, associated with the three Fracture Mechanics modes, are introduced (see Fig. 2).

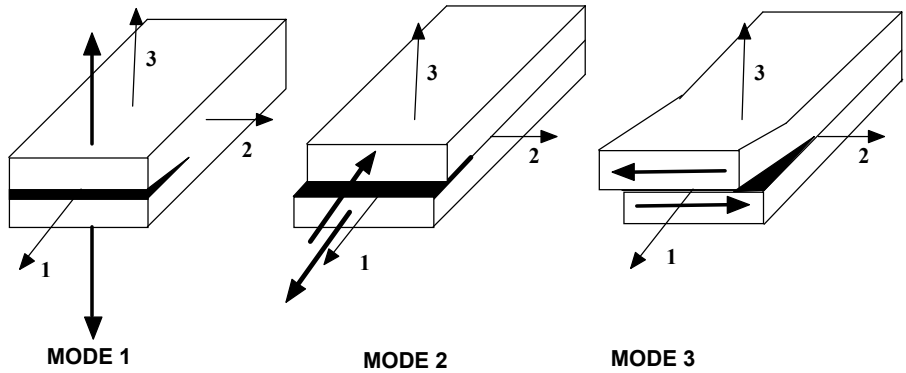

Fig. 2: Fracture Mechanics modes

where k_i^0 is an interlaminar stiffness value and d_i the internal damage indicator associated with its Fracture Mechanics mode, while subscript i corresponds to an orthotropic direction of the interface (see Fig. 2). Classically, the damage energy release rates, associated with the dissipated energy ϕ by damage and by unit area, are introduced as:

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

and

$$\phi = Y_{d_3}\dot{d}_3 + Y_{d_1}\dot{d}_1 + Y_{d_2}\dot{d}_2 \qquad (3)$$

with (3) to satisfy the Clausius-Duheim inequality. In what follows, an "isotropic" damage evolution law is described. In this model, as proposed in [14], the damage evolution law is assumed to be governed by means of an equivalent damage energy release rate of the following form:

$$\underline{Y}(t) = \sup \Big|_{\tau \leq t} \left[\left((Y_{d3})^{\alpha} + (\gamma_1 Y_{d1})^{\alpha} + (\gamma_2 Y_{d2})^{\alpha} \right)^{1/\alpha}_{\wedge\tau} \right] \tag{4}$$

The evolution of the damage indicators is thus assumed to be strongly coupled. γ_1, γ_2 and α are material parameters. A damage evolution law is then defined by the choice of a material function ω, such that:

$$d_3 = d_1 = d_2 = \omega(\underline{Y}) \text{ if } d_3 < 1 \quad ; \text{ and } d_3 = d_1 = d_2 = 1 \text{ otherwise} \tag{5}$$

One simple case, used for application purposes, is:

$$\omega(\underline{Y}) = \left[\frac{n}{n+1} \frac{<\underline{Y}-Y_o>+}{Y_c - Y_o} \right]^n \tag{6}$$

where a critical value Y_c and a threshold value Y_o are introduced. High values of the n case correspond to a brittle interface. To summarize, the damage evolution law is defined by means of the six intrinsic material parameters Y_c,Y_o, γ_1, γ_2, α and n. It will be shown in the next paragraph that Y_c, γ_1, γ_2 and α are all related to the critical energy release rates. The high values of the "n" case correspond to a brittle interface.

Links with Fracture Mechanics

A simple way of comparing Damage Mechanics with Linear Elastic Fracture Mechanics is to compare the mechanical dissipation yielded by the two approaches. This was performed in [13] and only the results are presented below. In the case of pure-mode situations, when the critical energy release rate reaches its stabilised value at the propagation denoted by (7), we obtain:

$$G^p_{c\,\mathrm{I}} = Y_c \; ; \quad G^p_{c\,\mathrm{II}} = \frac{Y_c}{\gamma_1} \; ; \quad G^p_{c\,\mathrm{III}} = \frac{Y_c}{\gamma_2} \tag{7}$$

For a mixed-mode loading situation, we simply derive a standard LEFM model:

$$\left(\frac{G_{\mathrm{I}}}{G^p_{c\mathrm{I}}} \right)^{\alpha} + \left(\frac{G_{\mathrm{II}}}{G^p_{c\mathrm{II}}} \right)^{\alpha} + \left(\frac{G_{\mathrm{III}}}{G^p_{c\mathrm{III}}} \right)^{\alpha} = 1 \tag{8}$$

wherein α governs the shape of the failure locus in the mixed mode. The identification of this interface model for the M55J/M118 material is given in [15].

Damage model with delay effects

It is well known that classical damage models lead inevitably to strain softening responses. From a fundamental point of view, this effect poses some severe mathematical difficulties that are now well understood. From a computational perspective, the numerical solution with classical local damage models exhibits a severe mesh dependence in the presence of strain softening, which leads to completely useless results. One way to avoid such difficulties is to use localization-limiter models. A large class of limiter models has been proposed. In order

to obtain, in all cases, a consistent model for the description of rupture, a variant of the previous damage model, that introduces delay effects is applied [16][17] [18]. In quasi-static problems, the use of such damage evolution laws implicitly introduces a length scale into the governing equations of the problem and then avoids the pathological mesh sensitivity for composite structures. This variant damage model ensures both that the physical variation of the driving force Y does not lead to an instantaneous variation of damage variable d_3 and that the damage rate is bounded. More precisely, the rate of the damage indicator is defined by:

$$Y(t) = \left[\left((Y_{d3})^{\alpha} + (\gamma_1 Y_{d1})^{\alpha} + (\gamma_2 Y_{d2})^{\alpha} \right)^{1/\alpha}_{\wedge\tau} \right] \qquad (9)$$

$$\dot{d}_3 = k < \omega(Y) - d_3 >^{n}_{+} \quad \text{if } d_3<1; \quad d_3=1 \text{ otherwise}$$

with $\omega(Y) < 1$; $w(Y) = 1$ otherwise

$$\dot{d}_1 = \dot{d}_2 = \dot{d}_3 \qquad \text{if } d_1<1;\ d_1=1$$

In many practical situations, a model without delay effect is sufficient. This is the case, in particular, for problems where the crack is described by a line. For example, in the case of a Double-Cantilever Beam (DCB) test, results are mesh-independent. But in the general case (three-dimensional delamination shape), the delay effect model must be used to unforced for example the mesh independence. In the case of the DCB fracture mechanics test, it is possible to identify the parameter k (inverse of a characteristic time Fig. 3) which governs the strain-softening response.

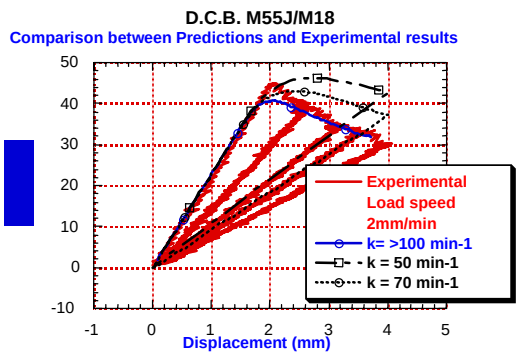

Fig. 3: Identification of the damage delay effect's characteristic time parameter (k=100min-^{1}).

F.E. implementation of the delay effect model

In this work, solid mechanics problems are solved by means of the finite element displacement method. The predictions are obtained with an extended version of the Finite Element code Castem 2000 (C.E.A.) [11] developed specifically for laminate composite structures. The principe of this method consists of solving, in an incremental way, the discretized equilibrium equations and the material governing equations. A special interface element of zero thickness has been used [19]. Here, we focus our attention on the implementation used to solve the delay effect damage model in the finite element code. An implicit Euler algorithm is employed, and the non-linear discretized damage equation is solved by the Newton Method. The numerical integration of the constitutive model is summarized in Table 1. A mode I prediction is shown in Fig. 4.

Table 1:

Delay Effect Damage Model Implementation: an implicit Euler algorithm is employed.

1. *Compute* $\omega(Y_{n+1})$
2. *Initialize*

   $i = 0, \quad d_{3_{n+1}}^{i} = d_{3_n}$
3. *Check the residual :*

   $R_{n+1}^{i} = d_{3_{n+1}}^{i} - d_{3_n} - \Delta t\ k_3 < \omega(Y_{n+1}) - d_{3_{n+1}}^{i} >^{n}_{+}$
4. *Check for convergence :*

   If $R_{n+1}^{i} < Tol$, *Then* $d_{3_{n+1}} = d_{3_{n+1}}^{i+1}$ *Goto* 5.

   Else : $\Delta d_{3_{n+1}} = -R_{n+1}^{i}\left(\dfrac{\partial R_{n+1}^{i}}{\partial d_{3_{n+1}}}\right)^{-1}$; $\quad d_{3_{n+1}}^{i+1} = d_{3_{n+1}}^{i} + \Delta d_{3_{n+1}} \quad i = i+1$, *Goto* 3.
5. *Compute damages* d_1, d_2 *:*

   $d_{1_{n+1}} = d_{1_n} + (d_{3_{n+1}} - d_{3_n}) \quad d_{2_{n+1}} = d_{2_n} + (d_{3_{n+1}} - d_{3_n})$
6. *Compute stress :*

   $\sigma_{33_{n+1}} = k_3^0(1 - d_{3_{n+1}})[U_3]_{n+1}, \quad \sigma_{23_{n+1}} = k_2^0(1 - d_{2_{n+1}})[U_2]_{n+1} \quad \sigma_{13_{n+1}} = k_1^0(1 - d_{1_{n+1}})[U_1]_{n+1}$
7. *Update and exit.*

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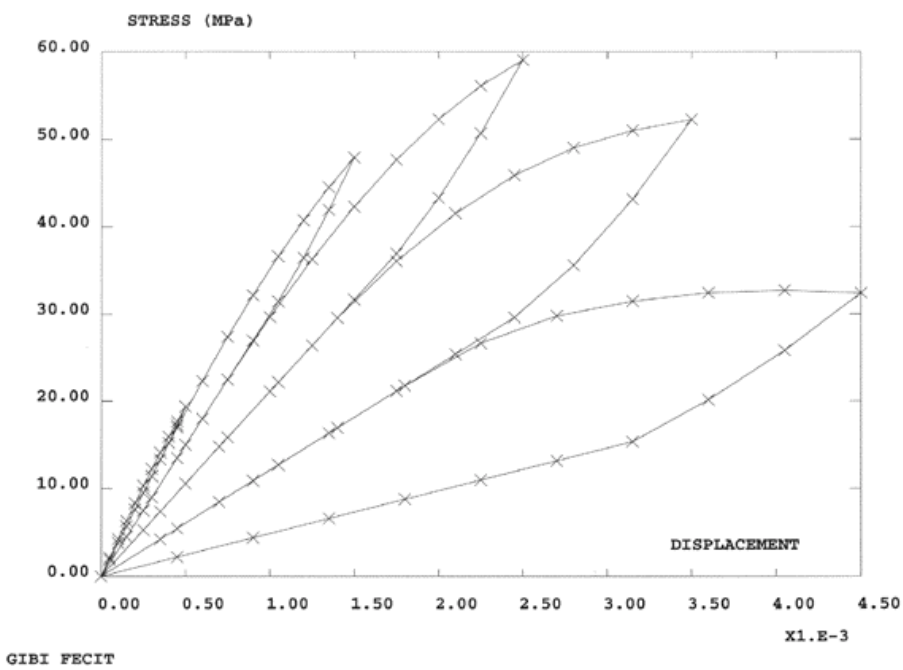

Fig. 4: Mode I prediction for damage delay effect's characteristic time parameter (k=40 min-1).

FINITE ELEMENT DAMAGE PREDICTION OF SPECIMEN TESTS

Several tests of delamination propagation: Double-Cantilevered Beam (DCB), Edge-Notched Flexure (ENF) and Mixed-Mode Flexure (MMF) or of initiation: edge delamination, are considered. In this study, crack growth and strain energy release rates are predicted and compared with experimental results obtained by the Aerospatiale Company for DCB, ENF and MMF tests Here we pay special attention to the basic aspects of finite element simulations of the inter laminar and intralaminar damages. Finite element prediction of classical Fracture Mechanics coupon tests are analyzed. A computation of the initiation and propagation of delamination, and more generally of laminated specimen test is presented and compared to the experiments. Tridimensional F.E. predictions of fracture mechanics specimen tests are conducted, the shape of the delaminaton front is also predicted. The tests of crack propagation in interlaminar fracture specimens are usually conducted on beam specimens with an initiated crack at the studied interface. Our specimens are 300 mm long and 20 mm wide. An anti-adhesive film 40 mm long and 25 mm in thickness is inserted at the mid-plane in order to initiate cracking. From an computational point of view, an interface of zero stiffness rigididy is used combined with unilateral contact conditions to model the initial crack (anti-adhesive film) in the F.E. predictions. The evolution of the damaged area is then refined for all test predictions. Experimental results and Finite Element predicted values exhibit good correlation (Fig. 5-6). In particular the lengths of the debonding area are found to be closed.

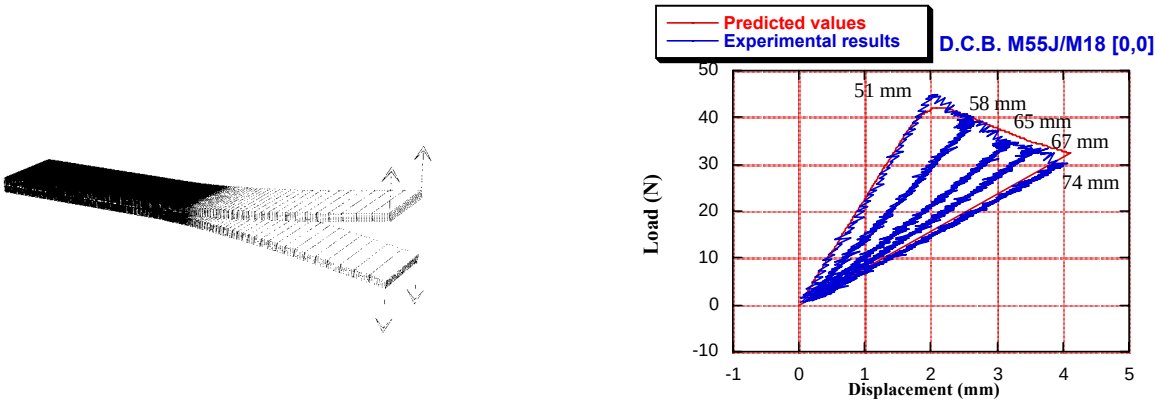

Fig. 5: F.E. Mesh of a D.C.B. specimen test. Evolution of the delamination area at the end of the test is 23mm. Prediction of a D.C.B. test . Comparison between experimental results and predicted values. The initial crack closure is 50 mm.

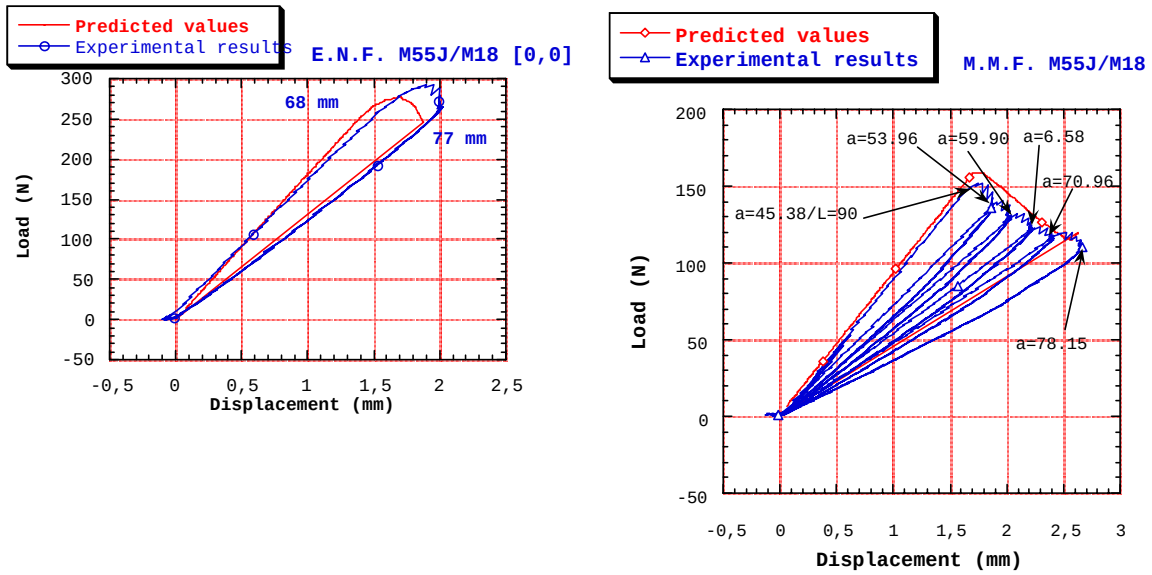

Fig. 6: Prediction of an E.N.F. test. Comparison between experimental results and predicted values. The initial crack closure is a=68mm. The evolution of the delaminattion area at the end of the test is 77mm. Prediction of an M.M.F. test. Comparison between experimental results and predicted values. The initial crack closure is a=45mm. The evolution of the delaminattion area at the end of the test is 32.77mm.

A computation of the initiation and propagation of delamination, and more generally of damages, in an M55J/M18 laminated plate is also presented and compared to the experimental data. Numerical simulations of delamination onset near the free edge of carbon-epoxy composite specimens under tension or compression have been previously studied. In this previous study, all of the damage phenomena were modeled as being concentrated on the interface. In this present work, the edge effects are computed by taking into account the damage modeling of both the interface and the layer. As another example of the possibilities of our F.E. code, let us consider the laminate structure defined in Fig. 7 where a tension loading is applied. These initial results have been obtained with the M55J/M18 material's parameters. During the loading history of the structure, a crack in the central interface (see Fig. 8)of the specimen test first appears; at the same time, cracks grow until rupture in the (+-45) layers. The usual mesh sensitivity difficulties are not present. Results are given in Fig. 7 and 8.

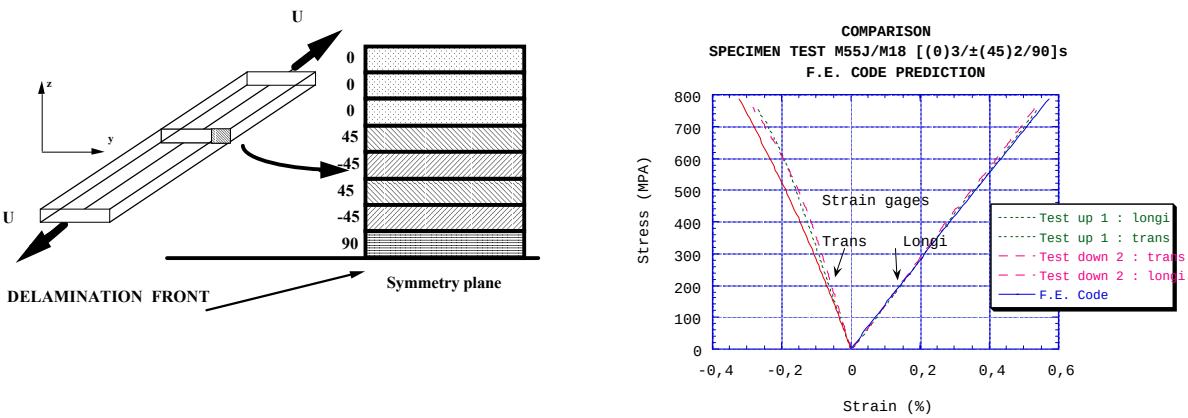

Fig. 7: the laminate is a [0_3, (+-45)$_2$, 90]sym M55J/M18 stacking sequence distribution layers. Response of the laminate and the F.E. prediction

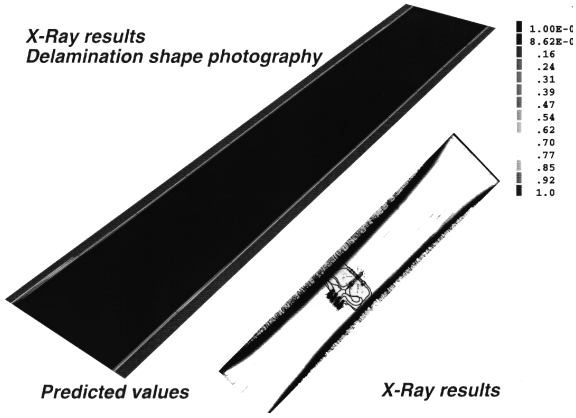

Fig.8: The laminate is a [0_3, (+-45)$_2$, 90]sym M55J/M18 stacking sequence distribution layers. Comparison between the prediction of the crack in the central interface of the specimen and X-ray delamination photography

CONCLUSIONS

A meso-damage mechanics modeling of laminates, whose aim is to predict the behavior of any composite structure with respect to delamination through knowing only a few characteristics of the interface, has been detailed. Predictions was conducted on M55J/M18 material specimens. Finite element examples show that this approach is promising in the prediction of delamination under various circumstances. Numerical tools, which allow the computation up to failure of the behaviour of any stacking sequence, was presented. This work represents the first step towards a global prediction of composite structures up to the complete fracture.

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