MICRO AND MESO COMPUTATIONAL DAMAGE MODELLINGS FOR DELAMINATION PREDICTION

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ABSTRACT

A major challenge in the design of composites is to calculate the intensities of the damage mechanisms at any point of a composite structure subjected to complex loading and at any time until final fracture as a result of strain and damage localization. Such final fracture mechanisms always involve delamination and most of the time lead to delamination macrocracks. The huge number of tests carried out on stratified composites in the aerospace industry shows the low level of confidence in models. A significant improvement in this situation, *i.e.* a drastic reduction in the number of industrial tests, could be achieved if one could create a real synergy among the approaches on different scales which, today, are followed quite independently of one another in the case of laminated composites. Deriving from numerous theoritical and experimental works carried out in micromechanics, one could introduce the microscale models. An intermediate scale called mesoscale enables to take into account the mechanisms of damage easily. However, there are only few links between the two scales. The questions discussed here are how to bridge the micro and mesomechanics of laminates and its impact to the micro and meso computational damage modellings for delamination prediction.

1 INTRODUCTION

The analysis of composite structures subjected to complex loading may require models to predict the intensities of the damage mechanisms and their evolution until final fracture. Even in the case of laminated composites (which are the most studied and, therefore, the best understood), the prediction of damage evolution up to and including final fracture remains a major challenge in the modern mechanics of composite materials and structures. The existing approaches are based either on refined concepts on the microscale (which thus, provide precise information on specific mechanisms, but whose formalisms do not convene for structural analysis), or on formalisms suitable for calculations (which, controversially, provide only very coarse and insufficient information on the micro nature of the degradations). The Damage Mesomodel for Laminates developed since twenty years at Cachan is one of those computational approaches. This model provides global measures of the degradation and no information on the microstate of degradation.

Therefore, recent works have focused on the development of bridges between the micro- and mesomechanics, in order to create a more robust damage mesomodel, providing more detailed information on the actual origin of the degradations. It is proved that there exists intrinsic operators which link the solutions on the two scales for any state of degradation. This legitimizes the description of these mechanisms on the mesoscale. On this basis, one can define a refined mesomodel using micro considerations.

An other multiscale approach, which is rather simple is called “computational damage micromodel”. Based on a semi-discrete and probabilistic description, this model is directly linked to the microscale and is able to take into account several mechanisms observed at microscopic level. However, this model leads to prohibitive calculation costs with the use of current industrial codes. The adaptation of a multiscale computational strategy is absolutely essential. Several point are mentioned in order to show the capabilities and the limitations of the different models.

2 MICRO AND MESO COMPUTATIONAL DAMAGE

2.1 The Damage Micromechanics of laminates

Up to now, there has been numerous theoretical and experimental works on the micromechanics of laminates (see Dvorak and Laws [1], Hashin [2], Nairn [3], Berthelot [4]); the micromechanics approach provides a relatively good understanding of damage mechanisms. However, these micromechanical models are lacking in some respects: in particular, they are far from being complete for the prediction of localization and final fracture.

In order to establish micro-meso relations, five degradation mechanisms are clearly identified on the microscale : diffuse damage in both the ply and the interface, transverse microcracking, local delamination and fibers breakage (see figure 1). The diffuse damage is associated mainly with fiber-matrix debonding, fundamental mechanism in order to explain the behaviour of the ply and often unused by micromechanical analysis. Transverse cracks are assumed to span the entire thickness of the ply. At the tip of the transverse microcracks, interface's degradations initiate.

In most practical cases, damage is firstly initiated by diffuse damage. Then, the accumulation of fiber-matrix debonding instances followed by their coalescence leads to transverse microcracking. The competition between transverse microcracking and diffuse delamination ends with the saturation of transverse microcracking and is relayed by the development of local delamination, which can lead to macroscopic interlaminar debonding.

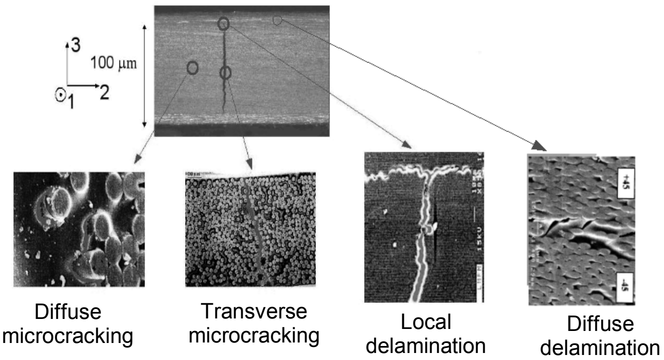

Figure 1 : The mechanisms of the degradations at the microscale

2.2 The Damage Mesomechanics of Laminates (DML)

One of the computational approaches which can be applied to laminated composites is based on what we call a "damage mesomodel for laminates" (see Ladeveze, Allix et al. [5],[6],[7],[8]) and also Talreja [9] for alternative approaches). In this approach, one assumes that the behavior of any laminated composite for any loading and any stacking sequence can be modeled using two elementary constituents which are continuous media: the ply and the interface (see figure 2).

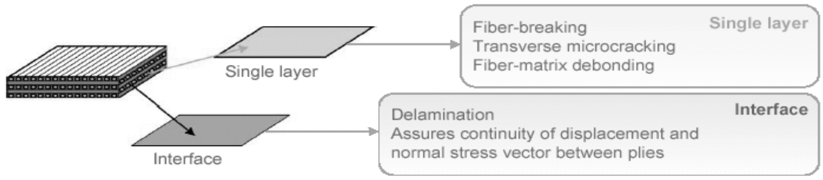

Figure 2 : The modelling of the laminate on the mesoscale

The ply takes into account diffuse damage, transverse microcracking, local delamination and fiber breakage. The interface is a surface entity representing the thin layer of matrix which exists between two adjacent plies and is characterized by their relative orientation. Its stiffness is equal to the shear modulus of the matrix divided by its thickness which is taken, by assumption, as the thickness of an elementary ply divided by 10. The interface provides for the transfer of strains and stresses between plies. The level of each mesoconstituent is quantified by damage indicators, whose evolution is governed by damage forces through an assumed damage law. An important point of the model is that the state of damage is assumed to remain constant throughout the thickness of a single layer (of course, it can vary from one layer of the laminate to the next). In other word, the main hypothesis of this computational model is that the damage evolution law is intrinsic to a ply and does not depend on the stacking sequence in which the ply is placed. In this classical version of the D.M.L, the indicators of damage are only global measures of the degradation which provide no information on the micro state of degradation. Several examples have been treated using the D.M.L (see Allix [8]).

2.3 Toward a bridge between micro and mesomechanics

The central question we aim to discuss here is : how can one bridge the micro and mesomechanics of damage? The belief that such a complete bridge could exist is not shared by all the people working in micromechanics. A first attempt at building such a bridge was made in (Ladeveze and Lubineau [10], [11]) for plane macrostresses. The mesomodel was found to be fully compatible with the microdamage mechanisms. The micro-meso relations introduce quantities or relations which we call “approximately ply-material”, which are intrinsically related to the cracked ply's characteristics and, therefore, independent of the characteristics of the other plies. Recently, additional work has extended this approach to out-of-plane stresses (e.g. Ladeveze et al. [12]). This more complex situation involves non-local mesomodels, as there are interactions between the interface's damage and the microcracking mechanisms of the adjacent plies. The method of investigation is now entering what is called a “virtual testing” stage, in which numerous numerical experiments using the micromodel and involving various possible stacking sequences, thicknesses,... are performed.

The link between the micro and meso scales requires the resolution of two basic problems. The first problem, which concerns the homogenized single layer, is an extension of the former 2D-ply problem to non-plane stresses. The second one, which concerns the homogenized interface, is a new 3D problem. A fundamental link between the micro and meso scales exists for both problems : two mesoquantities (the plane part of the mesostrains and the out-of-plane part of the mesostress) can be interpreted as mean values of the corresponding microquantities.

The objective is to build a continuum damage mechanics model which is quasi equivalent, from an energy standpoint, to the damaged laminate micromodel. Consequently, the potential energy stored in any part of a complete structure must be the same on the microscale and on the mesoscale, as illustrated in figure 3.

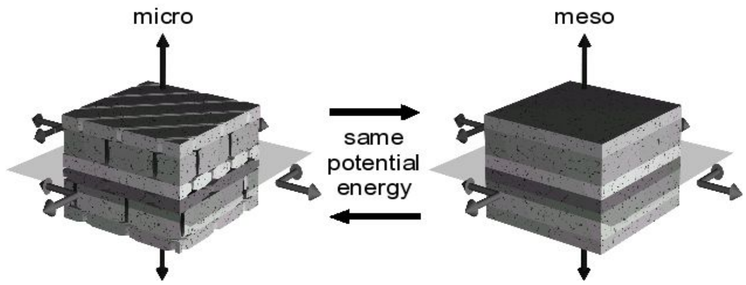

Figure. 3. Energy equivalence between the micro and meso interpretations of damage

The micromodel is characterized by periodic micro patterns, at least locally, which is consistent with most practical situations. The level of microcracking is quantified by a cracking rate ρ defined by ρ=L/H (ρ ∈ [0;0.7]). The local delamination is described at each transverse crack tip by a local delamination ratio τ = R/H (τ ∈ [0;0.4]) (see figure 4).

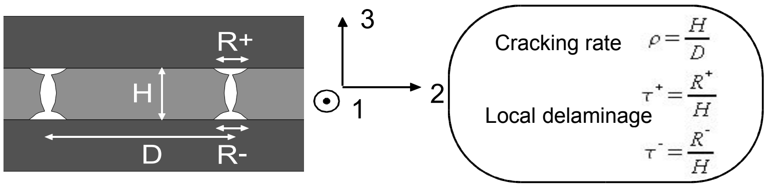

Figure 4 : Parameters of the micromodel

From experiments, the material can be considered as fully damaged for higher level of degradation. The evolution of these microvariables is governed by energy release rates in the frameworks of fracture mechanics or finite fracture mechanics.

The equivalent mesomodel is considered to be completely achieved if two basic situations of equivalence are established, one for the ply and one for the interface (see figure 5a) and 6). The determination of the potential energy of the domain on the microscale involves the calculation of the stress field at any point of the domain. The homogenization must be carried out for any stacking sequence defined by the thicknesses and orientations of the plies, but also for any kind of microdamage state.

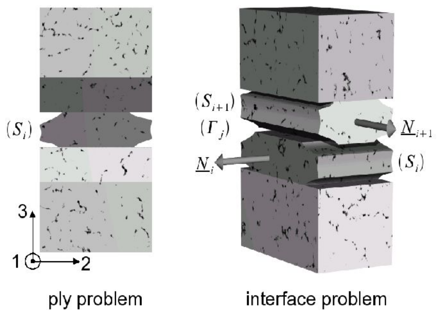

Figure. 5. a) Basic ply and b) interface problems

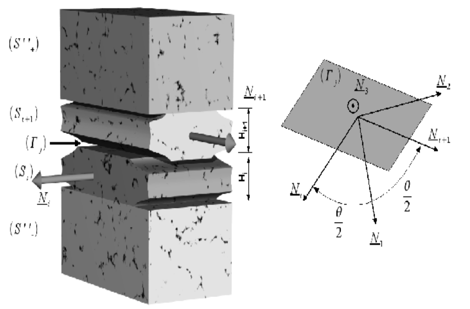

Figure. 6. The basic interface problem and corresponding notations

As previously stated, the traditional basic problem defines only the state of damage of ply S. This procedure gives excellent results for in-plane stresses because the energy is really confined to the ply S. In the case of out-of-plane stresses, however, the damage state of ply S induces some non-negligible energy in plies S'_- and S'_+. Consequently, the damage state of the ply being considered depends on the state of damage of the adjacent plies. To handle these considerations, one defines an extended ply problem, illustrated in Figure 5b). It is a 3D problem with periodic conditions which can be approximated by two 2D problems.

Prior to carrying out any identification between the micro- and meso-operators, one must verify the consistency of the homogenized operator with the hypotheses of the mesomodel. Numerical simulations made for a given set of interface parameters ($\theta, H_i/H_j, H_{i+1}/H_j$) shew that the identified damage indicators does not depend on the stacking sequence with a very good accuracy (<5%).

2.4 The multiscale approach and some applications

2.4.1 An improved damage mesomodel
The question being discussed here is the impact of such a bridge on the micro- and mesomodels. A first attempt is to define an improved damage mesomodel for laminates allowing the calculation of the intensities of the damage micromechanisms. We present the main guidelines for the simulation of specimens where cracks initiate at the edge, then propagate across the width of the sample. In a given ply, microcracking state is assumed to be constant within elementary areas with height H (the thickness of the ply) and length L≈H, minimal length for which a crack described on the microscale can reach steady state. Simulations have been carried out in the cross sections of straight samples made of a carbon/epoxy material, subjected to a thermal initial loading, then a pure traction loading. The model can reproduce the main basic features of classical experimental results (see Boniface et al. [13], Crossman et al. [14], Lagattu and Lafarie-Frenot [15]).

2.4.2 A computational damage micromodel
A second approach is a "computational damage micromodel" which is rather simple, yet semi-discrete and probalistic; unfortunately, this model leads to prohibitive calculation costs. The computational damage micromodel suggested here, is based on finite fracture mechanics works at a micro level. Considering the micro degradations detailed in section 2.1, we define minimum surfaces of fracture both in the ply and the interfaces to simulate microcracking and local delamination (see figure 8).

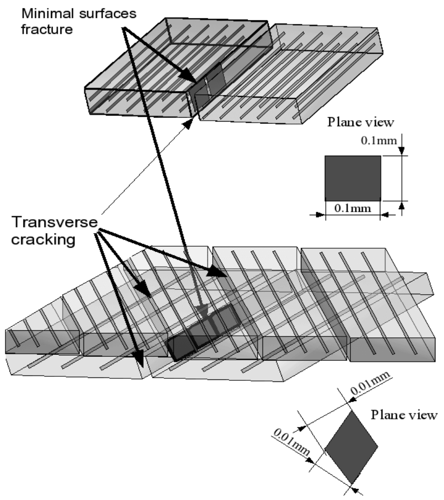

Figure 7 : Minimal surfaces of fracture

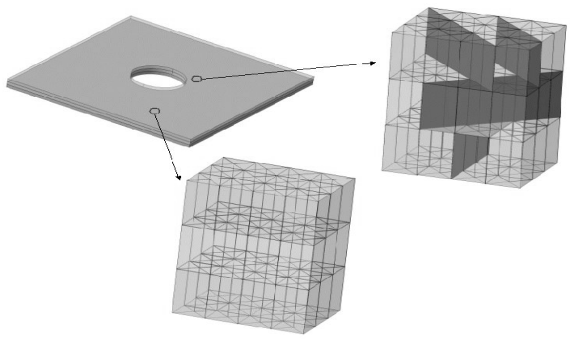

Figure. 8. Discrete model

So, it is a discrete modelling of the degradation within the laminate. This discrete standpoint leads to the creation of elementary cells within each ply (see figure 9). Such a model induces a very high number of cells and consequently, a huge number of degrees of freedom. Typically, for a 4 plies laminate whose size is 10mmx10mm, the computation cost requires about 10e9 tetrahedra.

2.4.3 Multiscale computational strategy
To simulate degradation for a laminate, it is absolutely essential to use a multiscale computational strategy. The idea is to adapt the multiscale strategy with time and space homogenization (see Ladeveze et al. [16]). The first step is to express the problem as an assembly of "cells" and "interfaces" (corresponding to the surfaces of fracture). Each of these components possesses its own

variables, equations and behaviour law. The simulation is then very robust ; in fact interfaces are assumed to have a binary behaviour : the interfaces are perfect when no degradation occurs and unilateral contact with friction is introduced when a degradation appears. The transition between perfect and contact interface will follow rules directly derived from the microscale. Furthermore, the computational strategy is based on the splitting of the interfaces traction and displacement in a macro and a micro part. Macro part corresponds approximately to the mean values for tractions and displacements. Then, using an iterative strategy based on the so-called LATIN method initially proposed in 1985 (see Ladeveze [17]), we can solve at each iteration a family of linear independent problems for cells (micro problems) and a "macro" problem defined on the entire structure but dealing with macro quantities. The size of the problem is consequently divided by 10 to 100. However, the calculation cost of this problem remains prohibitive and some improvements are required. A third scale is introduced in order to approximate the macro problem which becomes reasonable for current computers architecture. An interpolation is made in order not to compute the solution for every cell, particularly in areas where there is no degradation. Using these two simplifications decreases significantly the calculation cost. 3D code has been developed for laminated composite and should enable us to compute some simple experimental tests.

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