DAMAGE MODELLING OF WOVEN COMPOSITES ON THE MICROSCALE AND MESOSCALE

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Abstract
The evolution of damage in a woven composite results from the interaction and competition among several elementary mechanisms, which are greatly influenced by the microstructure. Thus, in order to develop a model as close as possible to the physics, it is necessary to observe, understand and describe each mechanism on the most appropriate scale. This work extends the micro-meso bridge, previously developed for laminates made of unidirectional plies, to woven composites.

1. Introduction

In the past years high performance composite materials have taken an important place in aerospace applications. However the design methods are still based on experimental testing. The virtual testing whose objective is the exploitation of predictive models based on the physics of materials, represents a major challenge in composite structures design. The global mechanical behavior of a woven composite is greatly influenced by the mechanisms acting at lower scales.

The micro scale is characterized by a precise description of the woven architecture, on the other hand, on the meso scale the plies are considered as homogeneous. Actually, in woven composites, also the yarn scale exists. On this scale the detailed yarn microstructure (composed by fibers and matrix) is described. However this work is aiming to study the micro scale where the yarns are considered as homogeneous.

The objective is to build a micro model of a woven composite elementary cell. This model is used to perform static simulations to study the cracking kinetics at the micro scale and homogenization calculations to link the micro to the meso scale. As a matter of fact the micro model will be used in the context of the development of a bridge between the two scales, aiming to improve the existent meso damage models [1], on the basis of what it has already been done for the unidirectional composites [2, 3]. The meso scale is indeed the most suitable for structural calculations performed during the design of mechanical parts.

2. Micro model construction

The geometrical complexity of woven composites architecture implies the creation of a finite elements model of an elementary volume of material, which enables to study the discrete damage mechanisms. This numerical model is built basing on the real material geometry in order to perform simulations on a model as close as possible to reality.

A first experimental analysis is carried on in order to identify, with microscopic observations, the geometrical characteristics of the material. The transverse and longitudinal yarn sections are measured and their variability along the fibers direction is observed. The micro model of the woven elementary cell is then developed in Abaqus using a geometry built basing on the measured parameters.

The geometry has been created with the tool GeoTis [4]. It is characterized by compatible surfaces between the parts and therefore it enables to manage the contacts between yarns and between yarns and complementary matrix. Yarns are considered as homogeneous orthotropic solids. The principal orthotropic directions follow the yarns undulation. Moreover the model meshing has been realized with great care. As a matter of fact, a hexahedral mesh has been created on the yarns in order to keep a good results precision on the parts where the principal microcracking mechanisms take place. Furthermore, the mesh is compatible [5] at the interfaces between yarns in order to be able to properly manage the contact and the possible delamination inter-yarns. This is a key point of this work, not always dealt with in literature. Finally two homogenized plies are built around the elementary woven cell to simulate the presence of the external plies in the composite.

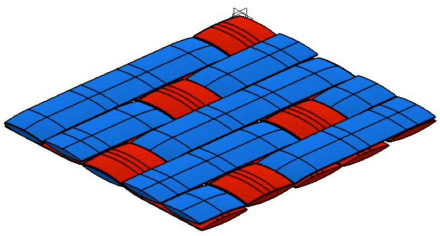

Figure 1. Geometry of the 5H Satin micro RVE ply without complementary matrix.

Fibers		Matrix	
Longitudinal modulus [GPa]	230	Young modulus [GPa]	3.20
Transverse modulus [GPa]	21	Poisson ratio	0.4
Shear modulus [GPa]	8.3	Shear modulus [GPa]	1.14

Table 1. Fiber and matrix properties (from [6]).

E_l	193,75	GPa
E_t	11,11	GPa
ν_{lt}	0,28	-
G_{lt}	4,15	GPa

Table 2. Yarn elastic homogenized properties.

3. Microcracking analysis

Simulations of the micro cell are then performed. The discrete damage mechanisms are introduced in order to understand the microcracking kinetics through a strain energy release rate analysis.

$$G = -\frac{\Delta E}{A} \tag{1}$$

where ΔE is the strain energy difference between the healthy and the cracked solution, and A is the crack surface. Actually, the strain energy release rate gives information on the existence of sites that are energetically favorable to crack formation. The higher this value is, the higher will be the probability to create a crack. After an accurate finite fracture mechanics analysis described in details in [7, 8], it has been shown that transverse cracks propagate instantaneously on the whole yarn length and their formation is driven by the stochastic distribution of defects. The central part of the yarn thus seems to be energetically favorable to crack formation with respect to the yarn edges.

Introducing each time a new crack, the strain energy release rate evolution has been calculated with respect to the microcracking ratio. This variable has been defined for the case of unidirectional composites [2] as the ratio between the ply thickness and the intra-crack distance. For what concerns the woven composites it will be defined here as

$$\rho = \frac{Hn_c}{D} \tag{2}$$

where H is the average yarn thickness and D is the average intra-crack distance in the elementary cell. In order to simulate the microcracking kinetic for a given material, the critical strain energy release rate associated to mode I microcracking should be known. This can be identified knowing the experimental strain threshold for cracks accumulation, and performing a coupled thermo-mechanical simulation at this strain level in order to take into account the residual thermal stresses due to the material forming process.

Since no information on the microcracking density evolution were available for the studied material, experimental data from the literature [9] were used. In [9], a 8H Satin laminate made up of 6 plies was studied and the microcracking density was observed for each ply with respect of applied strain (Fig. 3). The first microcracks occur for relatively low strains (around 0.5%-0.75%) while significant accumulation begins at around 0.98%. Since the model proposed here describes crack accumulation, this value was taken to identify the critical strain energy release rate, which turned to be $G_c = 250 J/m^2$. As it can be seen, the simulation reproduces quite well the cracking accumulation phase and the associated crack densities.

4. Damage evolution on the meso scale

In this Section, the homogenization technique described in [7, 8] is applied to the study of the damage evolution at the mesoscale. The energy associated to the micromodel with a given density of discrete cracks is equalled to the energy of a mesomodel, in order to determine a mesoscale damage parameter. In order to achieve this, it is necessary to introduce a proper mesomodeling strategy for the woven ply. Due to the observed similarities with UD composites, it

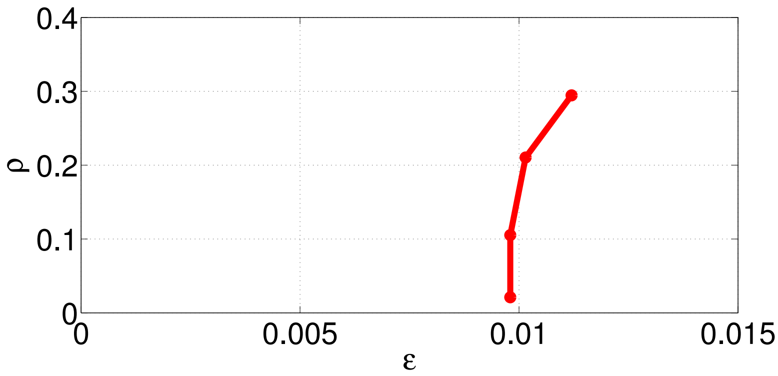

Figure 2. Microcracking ratio evolution with respect to applied strain.e

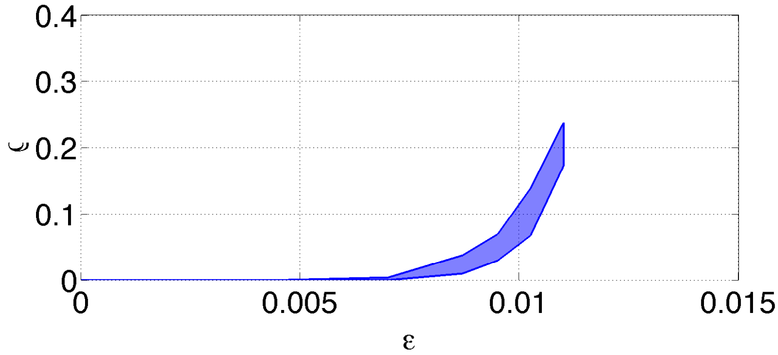

Figure 3. Experimental crack density evolution for a 8H satin 6 plies laminate [9]

has been chosen to model the woven ply as an equivalent [0/90°] laminate as shown in Fig. 4. This choice is consistent with the one done in the existing meso model for woven composites [1]. Therefore in the homogenization procedure the micro energy of transverse and longitu-

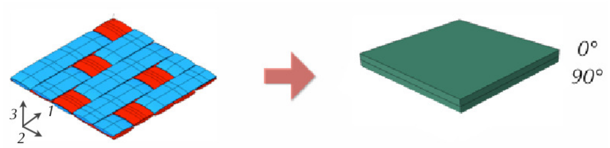

Figure 4. Woven-UD equivalence.

dinal yarns is used separately to retrieve the homogenized Young moduli of the 90° and 0° layers respectively. A meso damage variable d_{22} is introduced to take into account of transverse microcracking scenario affecting the transverse Young modulus of the equivalent 90° layer

$$d_{22}(\rho) = 1 - \frac{E_2^0}{E_2(\rho)} \tag{3}$$

where E_2^0 is the healthy ply transverse Young modulus and $E_2(\rho)$ is the one of the cracked ply.

For what concerns the shear meso damage, a variable d_{12} is introduced and it can be calculated as

$$d_{12}(\rho) = 1 - \frac{G_{12}^0}{G_{12}(\rho)} \tag{4}$$

where G^0_{12} is the healthy ply shear modulus and $G_{12}(\rho)$ is the one of the cracked ply.

The evolutions of the transverse (d_{22}) and shear (d_{12}) mesodamage parameters calculated here are compared to the ones previously calculated for a UD-based laminate [2] in Figs. 5 and 6. The behavior appears very similar in both cases. One should remember once again that the weave pattern considered is a 5H satin, in which significant portions of the unit cell can be considered analogous to two superposed UD plies.

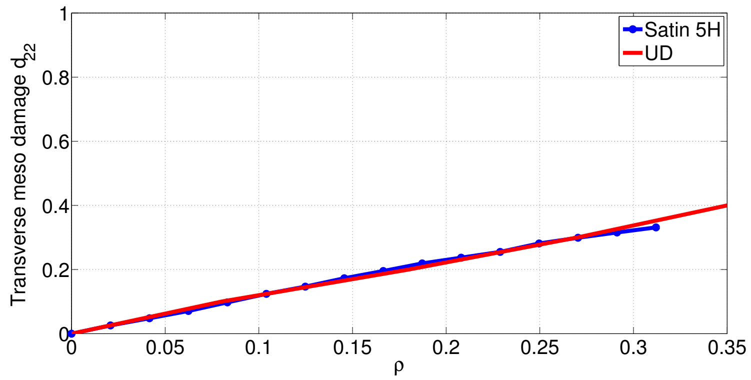

Figure 5. Meso damage variable evolution with respect to microcracking ratio, comparison with UD ply results [2].

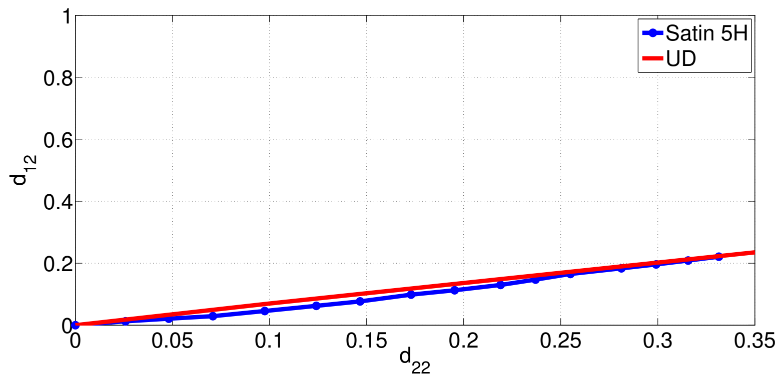

Figure 6. Shear meso damage evolution with respect to transverse damage, comparison with UD ply results [2].

5. Enhanced damage mesomodel

In the present section the meso damage model for woven composites will be enhanced exploiting damage evolutions and laws based on microscale computations, as it has already been done for UD-based laminates [10].

The strain energy for a degraded layer is written as:

$$e_d = \frac{1}{2}\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\end{bmatrix}^t [C] \begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\end{bmatrix} + \frac{\sigma_{12}^2}{2G^0_{12}(1-d_{12})(1-d)} + \frac{\sigma_{13}^2}{2G^0_{13}(1-d)} + \\ + \frac{\sigma_{23}^2}{2G^0_{23}(1-d_{23})(1-d)} \tag{5}$$

where $[C]$ is defined as

$$[C] = \begin{bmatrix} \frac{1}{E_1^0(1-d_f)} & -\frac{\nu_{12}^0}{E_1^0} & -\frac{\nu_{13}^0}{E_1^0} \\ -\frac{\nu_{12}^0}{E_1^0} & \frac{1}{E_2^0(1-[\sigma_{22}]_+ d_{22})(1-[\sigma_{22}]_+ d')} & -\frac{\nu_{23}^0}{E_2^0} \\ -\frac{\nu_{13}^0}{E_1^0} & -\frac{\nu_{23}^0}{E_2^0} & \frac{1}{E_3^0(1-[\sigma_{33}]_+ d')} \end{bmatrix} \quad (6)$$

where $[f]_+$ is the Heaviside step function, introduced in order to represent the irreversible nature of damage.
Damage along the fibers direction is called d_f. This represents the rupture of fibers, therefore its evolution is driven by a brittle law. The associated thermodynamic force is

$$Y_i = \frac{\partial \langle\langle e_d \rangle\rangle}{\partial d_i} \quad (7)$$

where $\langle\langle e_d \rangle\rangle$ is the average of the strain energy. The damage variable is driven by the following criterion

$$w = 1 \text{ if} \begin{cases} \sigma_{11} > 0 & \text{and} \frac{Y_{d_f}}{Y_f^t} \geq 1 \\ \sigma_{11} < 0 & \text{and} \frac{Y_{d_f}}{Y_f^c} \geq 1 \end{cases}, \quad w = 0 \text{ otherwise} \quad (8)$$

$$d_f = sup_{t \leq \tau}(w) \quad (9)$$

where Y_f^t and Y_f^c are the thermodynamic forces associated to fiber rupture in traction and compression respectively.
The diffuse damage variables are d and d' for tensile and shear loads respectively. The model used here is a continuum damage model firstly introduced in [11]. The thermodynamic forces associated with the damage variables can be written as

$$Y = \frac{\sigma_{22}^2}{E_2^0(1-d)^2} \quad (10)$$

$$Y' = \frac{\sigma_{12}^2}{2G_{12}^0(1-d')^2} \quad (11)$$

$$\tilde{Y} = Y + bY' \quad (12)$$

where b is a material property representing the coupling coefficient between tensile and shear behaviors. The damage evolution is a linear function of the thermodynamic force

$$d = sup_{t \leq \tau} \left(\frac{< \sqrt{\tilde{Y}} - \sqrt{Y_0} >_+}{\sqrt{Y_c} - \sqrt{Y_0}} \right), \; d' = bd \quad (13)$$

where Y_0 and Y_c are material properties and represent the thermodynamic forces associated to the damage threshold and the critical damage respectively.

The microcracking damage is identified by the meso variables d_{22}, d_{12} and d_{23} representing the damage for tensile and shear loads respectively.

The microcracking evolution is governed by an energy criterion. The strain energy release rate is written as

$$G = -\frac{\partial E_p}{\partial A} \tag{14}$$

where E_p is the potential energy of the damaged layer and A is the microcracks area. Therefore by combining equations 5, 14 and the microcracking ratio definition 2, the associated thermodynamic force can be written as

$$Y_\rho = \frac{\partial E_d}{\partial A} = LH\frac{\partial e_d}{\partial A} = H\frac{\partial e_d}{\partial \rho} \tag{15}$$

where L is the unit cell width and H is the yarn average thickness.

$$Y_\rho = \left[Y_{22}\frac{\partial d_{22}}{\partial \rho} + Y_{12}\frac{\partial d_{12}}{\partial \rho} + Y_{23}\frac{\partial d_{23}}{\partial \rho} \right] \tag{16}$$

Finally the rupture envelope can be written by introducing a mixed criterion based on the critical strain energy release rates G_I^c, G_{II}^c and G_{III}^c for mode-I, mode-II and mode-III respectively.

$$\left[\left(\frac{Y_{22}\frac{\partial d_{22}}{\partial \rho}}{G_I^c} \right)^\alpha + \left(\frac{Y_{12}\frac{\partial d_{12}}{\partial \rho}}{G_{II}^c} \right)^\alpha + \left(\frac{Y_{23}\frac{\partial d_{23}}{\partial \rho}}{G_{III}^c} \right)^\alpha \right]^{\frac{1}{\alpha}} \leq 1 \tag{17}$$

The meso damage variables are function of the microcracking ratio ρ through the micro-meso relationships established with homogenization of the micro model computations.

$$\begin{cases} d_{22} = f_{22}(\rho) \\ d_{12} = f_{12}(\rho) \\ d_{23} = f_{23}(\rho) \end{cases} \tag{18}$$

6. Conclusions and perspectives

This study was focused on the construction of micro-meso relations to enhance the existing damage meso model for 2D woven composites. In particular, the investigation of the ply problem mechanisms was carried on.

A numerical model of the woven composite microstructure was developed based on the real material geometry as detailed in [7, 8]. A multi-cracking analysis was carried on and the strain energy release rate evolution was found with respect to microcracking ratio. Then the evolution of the latter with respect to the applied strain was calculated, allowing us to simulate the kinetics of transverse microcracking.

Then, applying a suitable homogenization technique [7, 8] to the cracked cell, the decay of the mesoscale mechanical properties was calculated as well as the evolution of the meso damage parameter with respect to the microcracking ratio. Both tensile and shear load cases were studied. The fiber/matrix debonding scenario was introduced using a diffuse damage model. Finally an enhanced damage meso model for woven composites was proposed starting from the hypothesis introduced in [1], and enriching the model with damage variables laws based on micromechanics.

In order to complete the micro-meso bridge, the two types of delamination susceptible to appear in woven composites (namely, inter-yarn and inter-ply delaminations) are currently under investigation. Both phenomena will be introduced and investigated at the microscale, then homogenized at the mesoscale by using the energy equivalence outlined here. Since delamination affects mainly the out-of-plane properties, an interface problem with out-of-plane loading of the unit cell will be introduced. Furthermore, two plies including a full three-dimensional description will be constructed around the inter-ply interface to be studied. The complete micro-meso bridge will finally lead to an enhanced damage mesomodel suitable for virtual testing.

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