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Damage modelling of a 4D carbon/carbon composite for high temperature application

Xavier Aubard[a], Christophe Cluzel[b,c], Laurent Guitard[b,*], Pierre Ladeveze[b]

[a]*Société Européenne de Propulsion - Le Haillan BP 37 33165 St Medard-en-Jalles, France*
[b]*Laboratoire de Mécanique et Technologie E.N.S. de Cachan/C.N.R.S./Univ. P. et M. Curie, 61, avenue du Président Wilson, 94235 Cachan Cedex, France*
[c]*IUT GMP EVRYCours Mrg Roméro 91000 Evry, France*

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Abstract

Damage mechanisms and inelastic mechanical phenomena are modeled to the macroscopic scale for multiaxial loading. The studied material is a 4D carbon–carbon composite comprising therefore four reinforcement directions. A very simple mathematical material model has been first derived for multiaxial loading as a consequence of some remarkable experimentally observed properties and the material geometry. The anisotropic continuum damage theory introduced by Ladevèze is used. To identify the material constants and functions characterizing the studied 4D C/C material is a rather difficult task: fiber debonding near the edges is very important for tensile tests. To go further in the test analysis, large finite element computations have been done introducing a meso-modelling of the composite specimen, the meso-constituents being the fiber yarns, the matrix blocks and the interfaces. Finally, the identified material model has been checked on various experiments.

Keywords: B. Composite; C. Mechanical properties; D. carbon

1. Introduction

The material under study, S.E.P. (Société Européenne de Propulsion)-SEPCARB 4D is a 4D carbon–carbon composite comprising four reinforcement directions parallel to the largest diagonals of a cube. This material, called SEPCARB 4D, is used in the throat nozzles of solid propulsion systems (Fig. 1) owing to its excellent thermo-mechanical properties and high resistance to ablation [1]. Structures made of SEPCARB 4D are submitted to very high thermal gradients (from 20 to 3000°C) as well as to complex mechanical stresses. The aim of this study is to accurately model the thermo-mechanical behavior of these materials, and in particular their damage mechanisms, in order to predict the response of industrial structures.

The macroscopic behavior of this material is highly anisotropic and non-linear. Several types of degradation are observed inside the material and near the edges. Studying these degradations at the micro scale seems to be infeasible because of the 4D structure of the material. A very simple mathematical model has first been derived for multiaxial loading as a consequence of some remarkable experimentally-observed properties and the material geometry. The anisotropic continuum damage mechanics theory introduced by Ladevèze [2] is applied, as in [5] with the central focus being to derive the simplest damage kinematics. Anelastic phenomena are taken into account by a plastic like model.

Identifying the material constants and functions characterizing the studied 4D C/C composite is a rather difficult task. Fiber debonding near the edge is very significant in tensile tests and affects the results of these tests. Proceeding further in the test analysis, a study of these edge effect phenomena is in progress. The model is still three-dimensional, but it takes into account the material heterogeneity and complicated architecture. As in [3,4], the model is developed at the meso-scale, intermediate between the macro scale of the structure and the micro scale of the fiber. For each meso-constituent (fiber yarns, matrix and interfaces), a mechanical model is used. To rebuild the specimen behavior from the meso

* Corresponding author.
E-mail address: guitard@lmt.ens-cachan.fr (L. Giutard).

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model, a method based on the asymptotic development theory for periodic media is carried out.

2. Material and main experimental feature

The reinforcement yarns (fibers/matrix) have variable diameters, which are typically between 1 and 3 mm. They are positioned in four directions parallel to the larger diagonals of a cube (Fig. 1). One defines the X, Y and Z axis oriented perpendicularly to the cube faces, with the base (X',Y',Z) obtained by a 45° rotation of (X,Y,Z) around Z and the vectors $\underline{R}_{i,i\in\{1,2,3,4\}}$ of the reinforcement directions.

This material has a non-linear anisotropic behavior, as shown in Fig. 2, where the presented experimental results (stress–longitudinal strain) were obtained in tension in directions X, X' and R_i at ambient temperature. For a loading in a direction of reinforcement, both transversal and longitudinal strains increase linearly with the stress until occurrence of brittle failure. Responses to tension with cycling stresses in the X- and X'-directions show behavior with damage and anelastic strains. Damage of the studied 4D composite is attributed mainly to the mechanisms of yarn/matrix interface degradation.

Results from tension tests in the X-direction on specimens with circular sections of different diameters (Fig. 3) show failure stress increases with the cross-section of the specimen.

The failure surface of the large cross-section specimen reveals two zones (Fig. 4):

- a rather flat central zone of yarn failure, and
- a peripheral zone approximately 15 mm in width showing an irregular surface with yarn debonding.

In contrast, the failure surface of the 10- and 30-mm diameter specimens seems to indicate only the presence

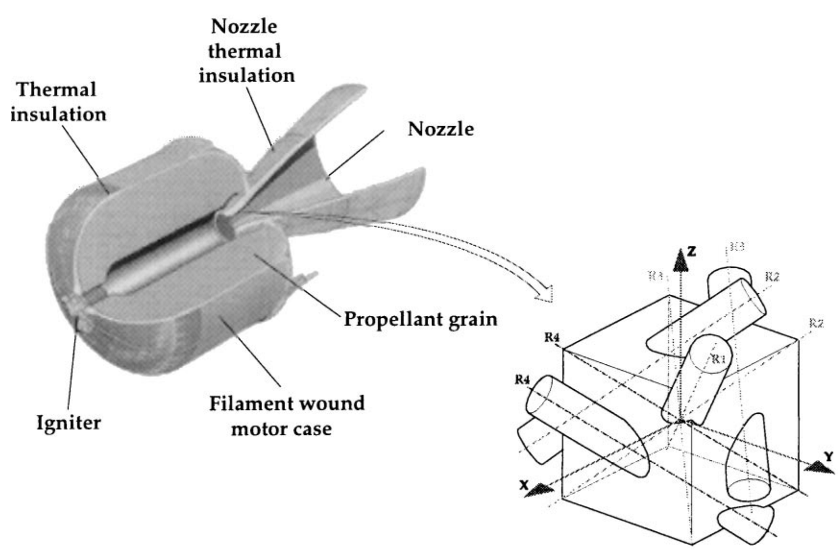

Fig. 1. Nozzle throat and Sepcarb 4D composite.

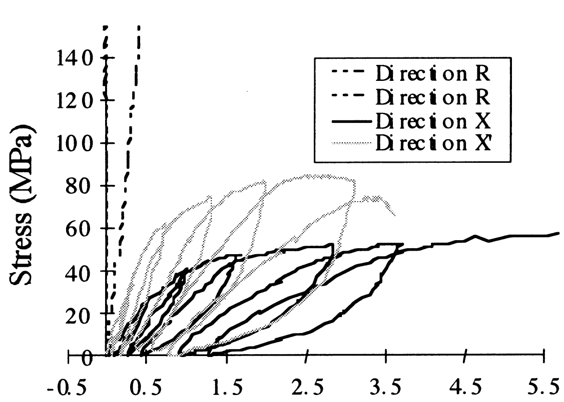

Fig. 2. Experimental responses of the internal behaviour obtained in tension in the X, X' and R directions.

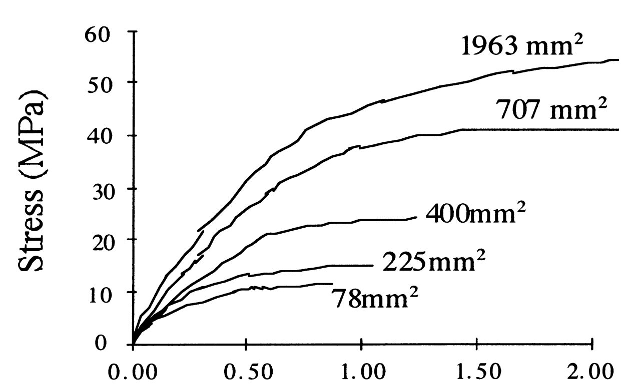

Fig. 3. Stress–strain curves of tension tests in the X-direction, at ambient temperature; influence of the specimen cross-section (S.E.P. results).

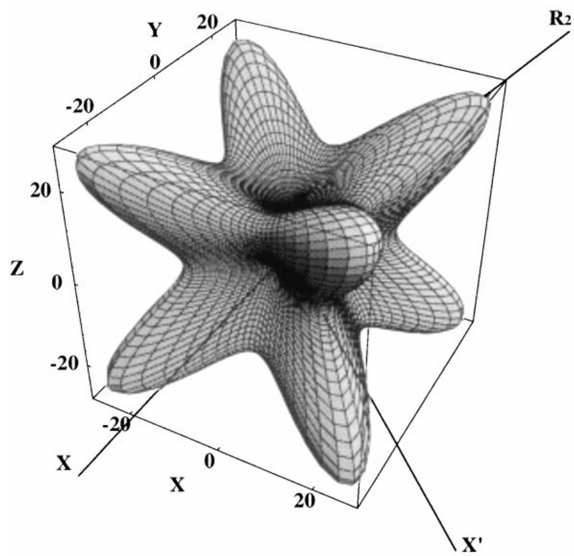

Fig. 4. Variation of Young's modulus; surface $E(\vec{n}).\vec{n}$.

of the zone of high debonding. These two zones allow assuming different variations for degradation occurring far from a free surface and near the edges. This phenomenon is attributed to the edge effect which modifies the stress distribution both in matrix and yarns close to a free surface.

To approach a model of the Sepcarb 4D mechanical behavior, one has to dissociate both the internal behavior and the yarn debonding initiated near the edges. The initial study, presented below, aims to model and identify, at the macroscopic scale, the "internal" behavior of Sepcarb 4D. The second study concerns more specifically the phenomenon of yarn debonding linking to free edge effects. In order to take into account the material heterogeneity and complex architecture, the model, such as in [3,4], is developed at the mesoscopic scale, intermediate between the macro scale of the structure and the micro scale of the fiber.

3. Macroscopic modeling of the far-edge Sepcarb 4D mechanical behavior

3.1. Hypotheses

This modeling approach is based on the responses obtained with the tension tests conducted on the large-section specimens. These different responses (Fig. 2) display the very high anisotropy of the mechanical behavior. This anisotropy is due to the reinforcement which are much stiffer than the matrix. Therefore, for a loading in a direction of reinforcement, it was obtained a linear evolution, until a brittle failure, of the transversal and longitudinal strains as a function of the longitudinal stress. Because of the symmetry of the yarn orientations, the Young's modulus is identical for each direction of reinforcement. Symmetries induced by the yarn orientations also impose the same material behavior for the directions X, Y and Z. Fig. 2 shows, for tension tests in these directions, a behavior with damage and anelastic strains.

3.2. Elastic behavior and damage phenomena

The description of the elastic part of the behavior of Sepcarb 4D is realized with the classical Hooke tensor with only three coefficients. Indeed, as the four directions of reinforcement have the same mechanical properties, symmetries show an elastic behavior of cubic type.

The surface representing the Young modulus in each space direction $E(\vec{n})$ is calculated from the Hooke tensor and represented in Fig. 4. One observes there the high anisotropy induced by the reinforcement dispositions.

Damage phenomena are also strongly anisotropic. As presented in Fig. 2, damage is blocked in a reinforcement direction, but exist for the other directions of the space.

Introducing the longitudinal and transversal linearity of the material's behavior for a tension load in a reinforcement direction, one demonstrates that only one damage variable is necessary to describe the degradation state of the material. The choice of the damage kinematics taking into account these experimental properties is realized using a representation of type barycentric made on the four vectors $\underline{R}_{i,i\in\{1,2,3,4\}}$ defining the directions of reinforcement. One shows [6] then that the elastic behavior can be completely defined with the following coefficients (where $\mathbf{K}$ is the Hooke tensor):

$$\mathrm{Tr}\left[\mathbf{K}^{-1}\cdot\left[\underline{\mathrm{R}}_i\cdot\underline{\mathrm{R}}_j^t\right]_{\mathrm{sym}}\cdot\left[\underline{\mathrm{R}}_k\cdot\underline{\mathrm{R}}_l^t\right]_{\mathrm{sym}}\right], (i,j,k,l)\in\{1,2,3,4\}^4$$

By introducing the conditions of symmetry, one obtains three independent coefficients which describe the elastic behavior:

$$a=\mathrm{Tr}\left[\mathbf{K}^{-1}\cdot\left[R_1\cdot R_1^t\right]\cdot\left[R_1\cdot R_1^t\right]\right],$$
$$d=\mathrm{Tr}\left[\mathbf{K}^{-1}\cdot\left[R_1\cdot R_1^t\right]\cdot\left[R_2\cdot R_2^t\right]\right],$$
$$e=\mathrm{Tr}\left[\mathbf{K}^{-1}\cdot\left[R_1\cdot R_2^t\right]_{\mathrm{sym}}\left[R_1\cdot R_2^t\right]_{\mathrm{sym}}\right]$$

That kind of approach allows taking into easily account experimental data. The coefficient "a" is the inverse of the Young modulus in a reinforcement direction. It is then a constant elastic parameter (called "a_0"). The coefficient "d" is linked to the X′R transverse coefficient. It is then constant too (called "d_0"). The choice of the damage kinematics is now evident. One has explicitly obtained an elastic parameter "e" which evolution can describe the material damage state. h is defined as a damage scalar coefficient, varying from 1 to infinity, equal to the fraction of the initial value of "e" to the value corresponding to a damage state of the material.

The thermodynamic force Y_h associated with the parameter h is defined classically by derivating the elastic strain energy of the damaged material. The state of damage with quasi-static loading is assumed to depend on the maximum force; one therefore has: $h = f(\underline{Y}_h)$, with: $\underline{Y}_h(t) = \sup_{\tau<t}(Y_h(\tau))$. The damage evolution law "$\underline{Y}_h \rightarrow h$" is an experimentally-identified material characteristic.

3.3. Anelastic strains modeling

The micro defect, i.e. the damage, leads to sliding with friction in the matrix and in the interfaces and thus to anelastic strains. We classically divide the strain into two parts, an elastic one and an anelastic one: $\varepsilon = \varepsilon_{\mathrm{el}} + \varepsilon_{\mathrm{an}}$. One way to model this anelasticity is to apply a plastic mechanical modeling. It is possible to obtain coupling between damage and analyticity phenomena. A notion which seems to work quite well is to build the model from quantities which are called "effective": the effective stress tensor $\tilde{\sigma}$ and the effective anelastic strain rate $\dot{\tilde{\varepsilon}}^p$ [7].

The effective stress is chosen; it defines the coupling between the classical stress and the damage state which is involved in anelastic strains. One particular choice which will be pursued herein is: $\tilde{\sigma} = \mathbf{K}_0.\mathbf{K}^{-1}\sigma$ with $\mathbf{K}_0$ the initial Hooke tensor.

The effective anelastic strain rate is defined from the anelastic dissipation in the following way:

$$\mathrm{Tr}[\tilde{\sigma}.\dot{\tilde{\varepsilon}}^p] = \mathrm{Tr}[\sigma.\dot{\varepsilon}^p].$$

The anelastic model results from the following hypotheses:

- the behavior in the four reinforcement directions is only elastic,
- the hardening is assumed to be isotropic, and
- the limit of the elastic domain is defined with an anisotropic threshold which is written: $f(\tilde{\sigma}, \tilde{R}) = \sqrt{\mathrm{Tr}[\mathbf{H}.\tilde{\sigma}.\tilde{\sigma}]} - \tilde{R}(\tilde{p}) - \tilde{R}_0$, with $\mathbf{H}$ being a fourth-order tensor which defines the coupling between the different stresses.

  By analogy with damage (like for damage, anelastic strains are blocked in the directions of reinforcements), a system of representation of the anelastic behavior is used with the reinforcement directions explicitly. The $\mathbf{H}$ tensor is then similar to the Hookeãs tensor. Introducing the blocking, which was experimentally observed, of the longitudinal and transversal anelastic strains for a loading in a given yarn direction, it can be shown in [6] that $\mathbf{H}$ is entirely defined with only one parameter and thus (where $\tilde{p}$ is the cumulated anelastic strain):

$$f(\tilde{\sigma}, \tilde{R}) = \sqrt{2(\tilde{\sigma}_{xx}^2 + \tilde{\sigma}_{yy}^2 + \tilde{\sigma}_{zz}^2 - \tilde{\sigma}_{xx}\tilde{\sigma}_{yy} - \tilde{\sigma}_{xx}\tilde{\sigma}_{zz} - \tilde{\sigma}_{yy}\tilde{\sigma}_{zz})} - \tilde{R}(\tilde{p}) - \tilde{R}_0$$

Anelastic flow law is obtained from the threshold function by:

$$\dot{\tilde{\varepsilon}}_{ij}^p = \dot{\tilde{p}} \frac{\partial f}{\partial \tilde{\sigma}_{ij}} |_{R=\mathrm{Cst}} \text{ with } \dot{p} \geqslant 0, f \leqslant 0 \text{ and } \dot{p}f = 0$$

The anelastic model is completely defined once the hardening function: "$\tilde{R}(\tilde{p}) + \tilde{R}_0$" has been experimentally identified.

3.4. Identification

The simplicity of the defined model allows carrying out the complete identification of the material parameters with only two tension cycling tests: the first one in a reinforcement direction, and the other one in the X-direction. For each cycle, one obtains the maximum value of the stress, the longitudinal strain and two transversal strains measured perpendicularly to the longitudinal direction.

With a test in a reinforcement direction, the values of the constant elastic parameters a_0 and d_0 are obtained. Transverse and longitudinal responses obtained from a tension test in the X-direction yield the value of the parameter "e" as well as its evolution.

For each unloading, *two* values of the variable h are derived, one taking into account the longitudinal elastic modulus, and the other taking into account the transverse elastic modulus (Fig. 5). Values of the associated variable Y_h are obtained from the maximum value of the stress for each unload. The hardening function is derived by calculating the values of "p" from the anelastic strain measures, along with the values of "$\tilde{R}(\tilde{p}) + \tilde{R}_0$" from the maximum value of the stress reached before each unload.

3.5. Simulations

The model has been identified and tested at S.E.P. for temperatures between 0 and 2500°C and introduced into the F.E. computation code MARC. It has been validated by different comparisons tests/calculations (four-point bending test, tube being submitted to an internal pressure). Fig. 6 presents results obtained both experimentally and numerically for a four-point-bending test conducted at 1000°C.

4. Study of the debonding phenomenon

4.1. Mesoscopic scale

Observations of the specimen failure surfaces and of the edge surfaces of the specimens show yarn debonding and slipping in the composite, respectively. The aim of this second study is to understand the origin and the evolution of this degradation in connection with the local redistribution of the stresses near a free surface. A study at a mesoscopic scale allows taking into account the composite structure (organization of the yarns) and easily modeling the mechanisms of degradation. Such an approach has already been used in the study of carbon/carbon composites such as 3D Aérolor [4] and 3D EVO [3]. These studies, carried out at the mesoscopic scale, have made it possible to understand the importance of the interface in composite material damage.

The description of the Sepcarb 4D at the mesoscopic scale uses three meso-constituents, which are:

- the yarns, cylindrical with a circular section,
- the matrix that fills the voids imposed by the presence of yarns in four directions (in the case of the Sepcarb 4D, the matrix has a continuous volume),
- the interfaces that transmit stresses between yarns and matrix.

For each meso-constituent a mechanical model is used. In each meso-constituent of the cells that define the structure, damage is held constant in a characteristic volume whose size is quite the yarn diameter. The model developed in this manner is thus consistent and the results of numerical computations are independent of the mesh. It is initially assumed that the major damage phenomenon is the yarn/matrix interfacial degradation. A brittle, transverse isotropic elastic model is therefore chosen for the yarn behavior and an isotropic elastic model for the matrix behavior. For the interface, results from many studies conducted on the problem of yarn/matrix interface debonding in composites [8–10] are utilized. The behavior is elastic with damage; totally damaged sliding with friction is modeled with Coulomb's law. A brittle damage threshold is chosen to characterize the interfacial degradation.

4.2. Reconstruction of a specimen's behavior in tension

In order to take into account experimental results that show the influences of a free edge, the structure chosen

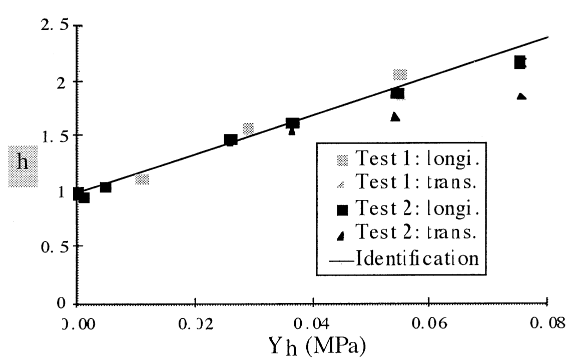

Fig. 5. Identification of the damage evolution law at ambient temperature.

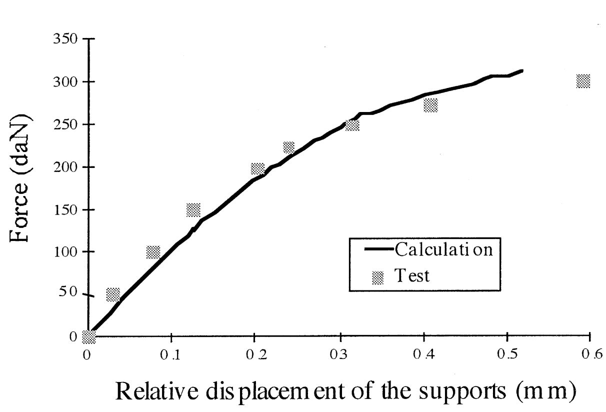

Fig. 6. Test/calculation results for a four-point bending test at 1000°C (S.E.P> results).

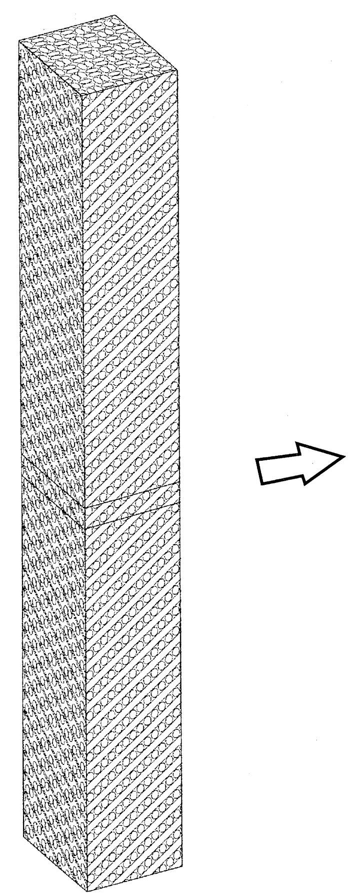

Fig. 7. Central zone of a specimen.

is the central area of a specimen (Fig. 7) loaded in tension/compression. The mechanical problem describing that kind of test is periodic in the longitudinal direction of the specimen. That propriety is used to reduce the calculated volume to just one period. The mechanical load is then defined from a homogenization technique for 1D-periodic beam in which an asymptotic development of the displacement is introduced. This kind of method, introduced in [11,12] and already used for other types of composites and structural geometry [3,4], is primarily intended to separate local effects (at the level of an elementary cell) from global effects (macroscopic loading).

The mechanical problem obtained is solved numerically by the F.E. method. Several sizes have been generated for the mesh of the meso-constituents. In order to use interface elements, the meshes of the different substructures (yarn and matrix) are rendered compatible. To study the influence of edge effects, the structure (a period of specimen's central zone) must be large enough. The finite-element discretized problem thus becomes very large in size (it can easily reach 200,000 d.o.f.). Moreover, it is non-linear due to the behavior (contact with friction) of both yarn/yarn and yarn/matrix interfaces. Applying a numerical method adapted to such problems then becomes necessary [13].

4.3. Mechanical characteristics of the meso-constituents

The yarn's longitudinal Youngãs modulus has been identified experimentally by S.E.P. [1]. Initially, in order to obtain values for the other mechanical characteristics of the meso-constituents, we relied on the values presented in [4], with respect to another carbon/carbon composite. The method of identifying the mechanical characteristics of the meso-constituents is similar to the one presented in [4]. Tests on sticks are in progress; a traction test will allow obtaining the longitudinal Young's modulus and Poisson ratio coefficient ν_{12} (with 1 being the longitudinal direction of a yarn). The value of the shear coefficient G_{12} is evaluated with a torsion test. The other elastic characteristics of the meso-constituents have been obtained from the initial macroscopic values of the material's elastic moduli, using a homogenization technique by the asymptotic development of 3D periodical media. The parameters in relation to the non-linear phenomena (failure criteria and friction coefficient of the interface) will be fitted using

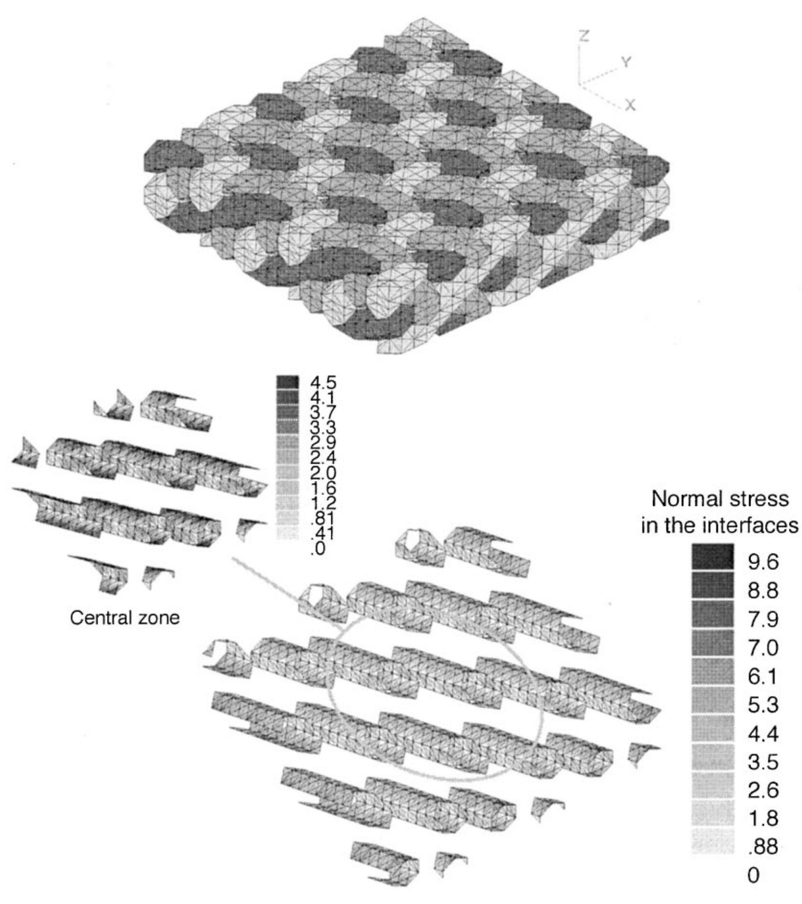

Fig. 8. Mesh of one periode of a specimen and normal stress in the interfaces rounding identically-oriented yarns.

the curves obtained with tension tests on specimens with different cross-sections.

5. Results

The first step is to study the major trends with respect to the two following extreme cases: a non damaged interface, and an interface that is almost totally damaged.

Results show a 50% loss in the longitudinal rigidity for the second case. Moreover, by introducing a non-damaged model for the interfaces (elastic interfaces), one obtains an evolution in the value of the normal stress in the yarns' interfaces between the edges and the heart of the section (Fig. 8). These stresses are higher near the edges than in the section's heart. This result is to be linked to the yarns' debonding phenomenon initiated near a free surface.

Introducing damageable interfaces, we obtain degradations on the interfaces near the edge of the structure. This damage lead to an evolution of the macroscopic rigidity. Interface threshold identification is in progress by comparison with experimental non-linear curves (Fig. 3).

6. Conclusions

The studied composite material, Sepcarb 4D, exhibits a mechanical behavior that differs depending on the proximity to a free surface.

An initial model of the internal mechanical behavior (far from a free surface) of Sepcarb 4D composites has been proposed and identified. In order to easily take into account the preferred directions which are the four reinforcements directions, a model of non-linear behavior has been developed using a system of barycentric coordinates. The elasto-plastic type model with damage thus obtained is very simple since it necessitates only three elastic coefficients, one curve to describe the damage evolution and one curve to describe anelasticity. The identification of this model necessitates only two tension tests, a test in a direction of reinforcement with longitudinal and transversal strain measures and an off-yarn axis test with a measure of the longitudinal strain.

From an experimental point of view the edge effect discribed below serves to disturb tension tests and makes it difficult to identify the mechanical macroscopic characteristics of the material.

In order to study this edge effect, the material is then described at a smaller scale, called the mesoscopic scale, which corresponds to the scale of the material constituents: the fiber yarns, the matrix and their interfaces. A simple model of the mechanical behavior of these meso-constituents is developed: brittle transverse isotropic elastic for the yarns, isotropic elastic for the matrix, and then elastic contact with friction after a brutal damage for the interfaces. With this model, some of the experimental observations of edge effects have been recorded. Experimental tests reveal a difference between tension and compression behavior. Such results are being used to identify the initial interfacial rigidity and the damage evolution law.

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