COMPOSITE BOUNDARY-EFFECTS COMPUTATIONAL MODELLING

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SUMMARY: This paper deals with problems of yarn debonding. Taking into account this type of damage is very important to predict the rupture of structures made with 4D Carbon/Carbon composite. This type of damage occurs principally in that material near free surfaces. This is due to an edge effect which modifies the local distribution of the stresses near a free surface. The study of this phenomenon is made at a meso scale with 3 constituents: the fibers, the matrix and the interfaces. A non-linear-damage model is introduced for the interface. Large scale F. E. calculations are done using special numerical methods adapted to such problems: a domain decomposition approach associated with the LATIN method.

KEYWORDS: 4D Carbon/Carbon – Damage mechanics – Computations – Edge effects

INTRODUCTION

The material under study was manufactured by S.E.P. (Société Européenne de Propulsion) and is a 4D Carbon-Carbon composite comprised of four reinforcement directions parallel to the largest diagonals of a cube. These materials, called SEPCARB 4D, are used in the throat nozzles of solid propulsion systems (Fig. 1) owing to their excellent thermo-mechanical properties and their high resistance to ablation [1]. Structures made of SEPCARB 4D are submitted to very high thermal gradients (from 20°C 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 material model has first been derived for multiaxial loading as a consequence of some remarkable experimentally-observed properties and material geometry. In order to easily take into account the preferred directions, which are the 4 directions of reinforcements, the model of non-linear behavior has been developed using a system of barycentric coordinates. The anisotropic continuum damage mechanics theory introduced by Ladevèze [2] is applied with the central focus being to derive the simplest damage kinematics. Anelastic phenomena are taken into account by a plastic like model whit isotropic hardening. The model obtained is very simple: it introduces only three elastic

parameters, one damage parameter and two functions: one for the damage evolution law, and a second one for the hardening behavior. That model is describes precisely in [3].
Identifying the material constants and functions characterizing the studied 4D CC composite is a rather difficult task. Fiber debonding near the edges 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. Preliminary modeling and results are given here. The model is still three-dimensional, but it takes into account the material heterogeneity and complicated architecture. As in [4-5], 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 model, a method based on the asymptotic theory for periodic media is carried out.

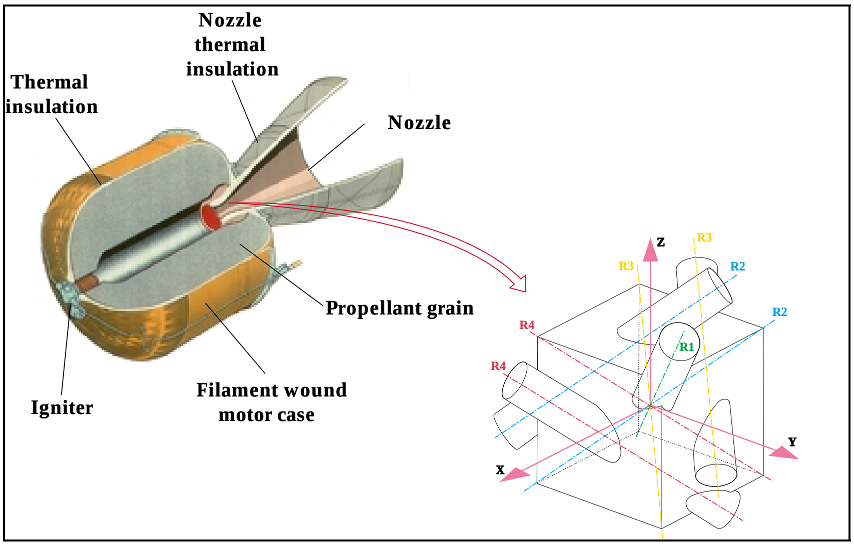

Figure 1: nozzle throat and Sepcarb 4D composite

MATERIAL AND MAIN EXPERIMENTAL FEATURE

The reinforcement yarns (fibers/matrix) have variable diameters, which are typically between 1 and 3mm. 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 $\underline{\mathbf{R}}_{i, i \in \{1,2,3,4\}}$ of the reinforcement directions.
This material has a non-linear anisotropic behavior, as shown in Figure 2, where the presented experimental results (stress versus longitudinal strain) were obtained in tension in directions X, X' and R_i to ambient temperature. For a loading in the direction of reinforcement, both transversal and longitudinal strains increase linearly with the stress until brittle failure occurs. Responses to tension with cycling stresses in the X and X' directions show behavior with damage and anelastic strains. Damage of the Sepcarb 4D is attributed mainly to the mechanisms of yarn/matrix interface degradation.
Results from tension tests conducted by S.E.P. in the X-direction on specimens with circular sections of different diameters (Fig. 3) show increases failure stress with increasing section dimension of the specimens.
The failure surface of the large section specimen reveals two zones (Fig. 4):

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

In contrast, the failure surface of the specimen with 10 and 30-mm diameters seems to indicate the absence of the rather flat zone. Thus the only visible zone is the peripheral one. 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.

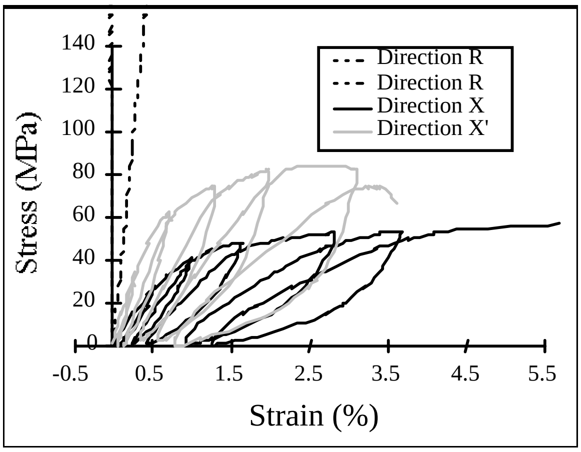

Figure 2: experimental responses of the internal behavior obtained in tension in the X, X' and R directions

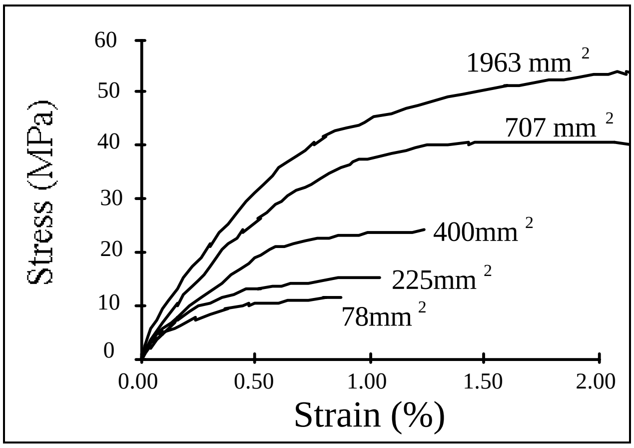

Figure 3: stress-strain curves of tension tests in the X-direction, at ambient temperature; influence of the size of specimen section (SEP results)

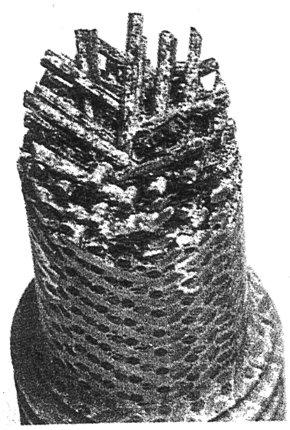

Figure 4a

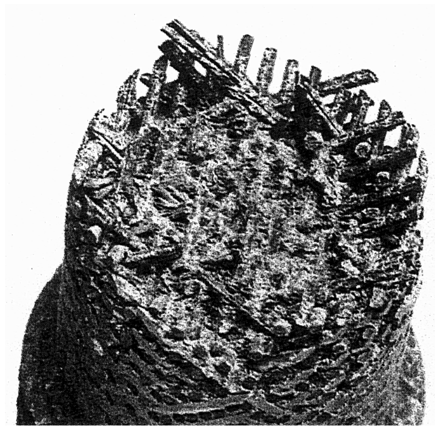

Figure 4b

Failure surface of a circular cylindrical specimen with a section diameter of 30mm (Fig.4a) and 50mm (Fig. 4b) (S.E.P.)

To formulate 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 in [3], aims to model and identify, at the macroscopic scale, the "internal" behavior of Sepcarb 4D. The second study, presented below, concerns 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 [4-5], is developed at the mesoscopic scale, intermediate scale between the macro scale of the structure and the micro scale of the fiber.

STUDY OF THE DEBONDING PHENOMENON

Mesoscopic scale

Observations of the failure surfaces and the edge surfaces of the specimens show a yarn debonding and slipping in the composite respectively. The aim of this second part of this 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 one to take into account the composite structure (organization of the yarns) and easily model

the mechanisms of degradation. Such an approach has already been used in the study of Carbon/Carbon composites such as 3D Aérolor [5] and 3D EVO [4]. 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 3 meso-constituents, which are:

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

Mechanical behavior of the meso-constituents

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 dimension is a material characteristic. 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 [6-8] are utilized. The behavior is elastic with damage; totally damaged sliding with friction is modeled with Coulomb's law.
Damage mechanics is used to model the behavior of the interfaces. They are orthotropic bi-dimensional entities. The behavior of damaged interfaces is described by the following strain energy:

$$Ed = \frac{1}{2}\left\{ \frac{\langle \sigma_N \rangle_+^2}{k_0(1-d_N)} + \frac{\langle \sigma_N \rangle_-^2}{k_0} + \frac{\vec{\sigma}_\tau^{\,2}}{k_0(1-d_\tau)} \right\} \tag{1}$$

where $\langle x \rangle_+$ represents the positive part of the variable x, d_N and d_τ are two scalar-damage variables and k_0 is the initial elastic modulus of the interface identical for both tension and shear.

Damage of the interface principally leads to propagation of cracks in the plane of the interfaces. Thus the behavior of a damaged interface loaded in tension is different than its behavior in compression. This explain the splitting of the strain energy into two parts: a strain energy for a state of tension and another for a state of compression. One defines the conjugate quantities of the damage variables:

$$Y_N = \left.\frac{\partial Ed}{\partial d_N}\right|_{\underline{\sigma} = Cst,\, d_\tau = Cst} = \frac{1}{2} k_0 \langle [\![U_N]\!] \rangle_+^2 \tag{2}$$
$$Y_\tau = \left.\frac{\partial Ed}{\partial d_\tau}\right|_{\underline{\sigma} = Cst,\, d_N = Cst} = \frac{1}{2} k_0 [\![\underline{U}_\tau]\!]^2$$

where $[\![X]\!]$ represents the discontinuity of the variable X through the interface.
The damage evolution laws are defined here after:

$$d_N = f(Y) \text{ with } Y = \sup_{\theta \le t} \sqrt{\tilde{Y}_N(\theta) + a\tilde{Y}_\tau(\theta)} \text{ and } d_\tau = b d_N. \tag{3}$$

where $\tilde{Y}$ is the average of the damage associated force in a characteristic surface of the interface. In fact, we use a damage model nearly equivalent to one with delay effect.

The parameters a and b introduce a coupling between the damage due to a loading into tension of the interface and a shear loading. As k_0, they are two model parameters to be identified.
The yarn's longitudinal Young’s 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 [5]. Tests on yarns are in progress; a traction test will provide 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 the curves obtained with tension tests on specimens with different cross-sections.

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 is the central area of a specimen (Fig. 5) loaded in tension/compression. The problem's periodicity in the longitudinal direction is then 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 [9,10] and already used for other types of composites and structural geometry [4,5], is primarily intended to separate local effects (at the level of an elementary cell) from global effects (macroscopic loading).

A method adapted to 1D periodic beams has been developed. The elementary dimensions of the section and the period are of the same order and can be considered small with respect to the length of the central zone.

One uses an asymptotic development of the displacement:

$$\underline{U} = \underline{U}_0 + \varepsilon \underline{U}_1 + \varepsilon^2 \underline{U}_2 + \ldots \tag{4}$$

For a tension/compression load in the longitudinal direction of the specimen, one can show that the first order of the strain is the strain of the homogenized beam. On the contrary, the first order of the stress is non constant through the elementary cell and is a second order displacement function:

$$\sigma_0 = \mathbf{K}^\alpha . \varepsilon_0\left(\underline{U}_0\right) + \mathbf{K}^\alpha . \varepsilon\left(\underline{U}_1\right) \tag{5}$$

where $\mathbf{K}^\alpha$ is the stiffness tensor defined at the local level for each meso-constituent α

The displacement $\underline{U}$ is obtained through the resolution of the following local problem (Fig. 6):

Find

$$\text{such at} : \forall\, \underline{U}^* \in \mathcal{V},\ \int_V \mathrm{Tr}\left[\mathbf{K}^\alpha . \varepsilon\left(\underline{U}_1\right) . \varepsilon\left(\underline{U}^*\right)\right] dV + \int_V \mathrm{Tr}\left[\mathbf{K}^\alpha . \varepsilon_0 . \varepsilon\left(\underline{U}^*\right)\right] dV. \tag{6}$$

with $\varepsilon_0 = \varepsilon_{NN} N.N^t$, where ε_{NN} is constant in V in the case of tension/compression, without coupling, in a direction N; this field define a volumetric load in each meso-constituent: $\mathbf{K}^\alpha . \varepsilon_0$.

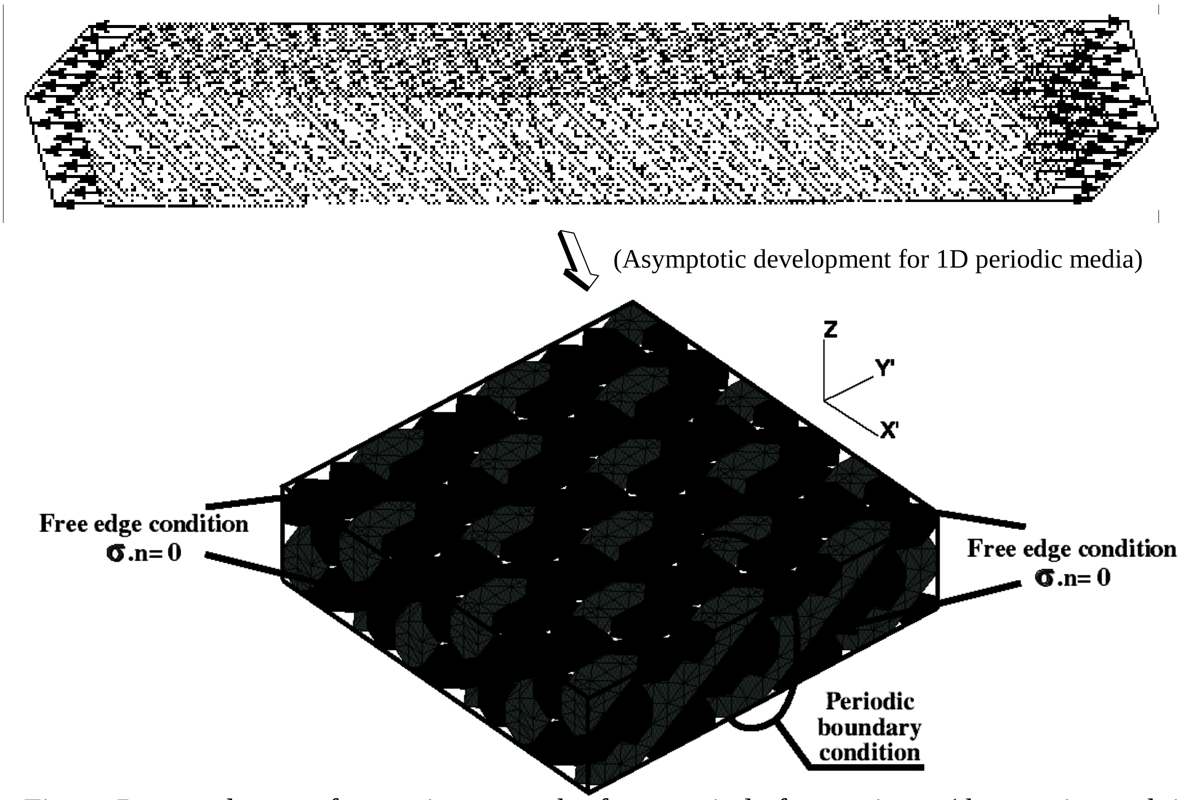

Figure 5: central zone of a specimen, mesh of one period of a specimen (the matrix mesh is not represented) and boundary conditions for one period of an Z oriented specimen

The average axial load of the specimen as the function of the strain is obtained with:

$$\text{Find } F = \frac{S}{V}\int_V N^t.\sigma_0.N \, dV \text{ avec S : section de l'éprouvette}. \tag{7}$$

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 (damage and contact with friction) of both yarn/yarn and yarn/matrix interfaces. Applying a numerical method adapted to such problems thus becomes necessary [11].

RESULTS

Influence of the edge effect on the interfaces' loading

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

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. 7). 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.

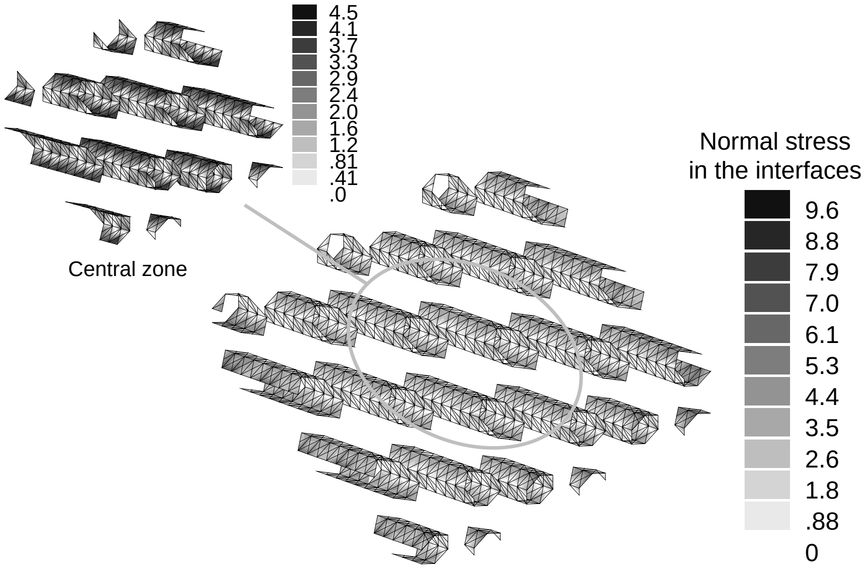

Figure7: normal stress in the interfaces rounding identically-oriented yarns

Specimen behavior calculations with damageable interfaces

The damageable elastic behavior of the interface presented in paragraph 4.2. is introduce here. In order to compute the non-linear behavior of the structure, one uses an incremental algorithm. The numerical method uses is explicit.

One assumes the state of the material (damage state of the interface) for a given magnitude of load. The problem defined in paragraph 4.3. is then solved for a load magnitude slightly larger. The state of the material as a function of the interface load is then modified. The increment of a load is small enough to obtain a result closed to the solution of the evolution problem. More other, the material is assumed to be undamaged in its base state.

We then obtain degradations of the interfaces near the edge of the structure. These degradations penetrate inside the section when the macroscopic load increases (Fig. 8). That type of damage evolution modifies the loading through the section of the meso-constituents and leads to a non-linearity of the macroscopic response of the specimen..

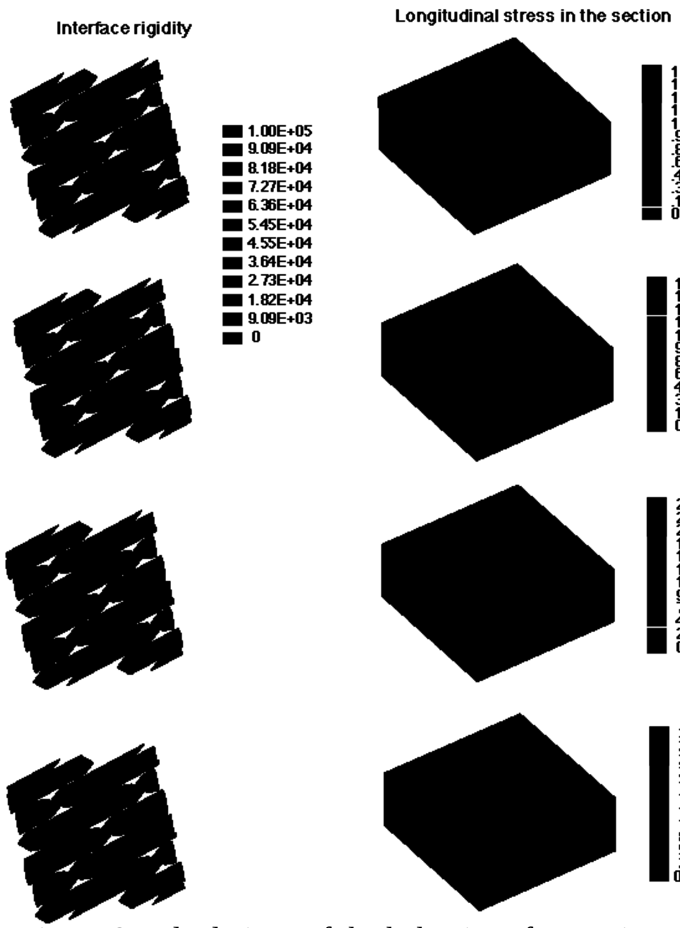

Figure 8: calculations of the behavior of a specimen loaded in tension;
evolution of the interface rigidity and the loading of one period of the specimen central zone

Calculations on several specimens with different section sizes show that this non-linearity depends on the size of specimen section. Interface damage-law identification is in progress by comparison with experimental non-linear curves (Fig. 3)

CONCLUSION

The studied composite material, Sepcarb 4D, exhibits a mechanical behavior that differs depending on the proximity to a free surface. From an experimental point of view the edge effect described below serves to disturb tension tests and makes it difficult to identify the mechanical macroscopic characteristics of the material. More generally, these debonding effects are present near the edges of 4D composite structures and then must be modeled and computed.

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 first 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 initially orthotropic elastic with damage and then contact with friction behavior for the interfaces. With this model, some of the experimental observations of edge effects have been recorded. To take into account damage in the heart of the specimen, a more evoluated model of the interface is in progress. Experimental tests reveal a difference between tensile and compressive behavior. Such results are being used to identify the initial interfacial rigidity and the damage evolution law.

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