AN ENHANCED COMPUTATIONAL MICROMODEL FOR CFRP LAMINATES

Michael Trovalet[1], Pierre Ladevèze[1,2], Gilles Lubineau[1]

[1]LMT-Cachan (ENS de Cachan/CNRS UMR8535/UPMC/Pres Universud Paris)
61, avenue du Président Wilson, F-94235 Cachan CEDEX, France
trovalet@lmt.ens-cachan.fr

[2] EADS Foundation Chair 'Advanced Computational Structural Mechanics'

ABSTRACT

This paper describes and illustrates a micromodel for CFRP laminates which couples micro and meso aspects. The introduction of both micromechanics and mesomechanics into a single, but hybrid description enables one to take into account discrete and diffuse degradation mechanisms on the appropriate scales. After a brief review of the model, the paper proposes an extension which consists in introducing plasticity and viscosity on the mesoscale. This improves the model by adding the most important types of behavior. In order to show the model's capabilities, it is run through a dedicated high-performance domain decomposition strategy based on an iterative resolution. Different stacking sequences are simulated and the results are compared with experimental data.

1. INTRODUCTION

Today, composite materials are involved in more and more high-performance applications, particularly in vital parts for the aeronautical industry. This is the reason why the prediction of the evolution of damage up to fracture is a crucial topic in the design of composite structures. An important challenge for the aeronautical industry today is to substitute numerical simulations, called virtual testing, for long and expensive experimental investigations. But a determining factor in making that change is one's level of confidence in the models, which must be very high.

In this context, a hybrid approach called the computational damage micromodel for laminated composites was proposed in [1]. This semi-discrete approach creates a synergy between the micromechanics [2], [3] and mesomechanics of laminates [4] ,[5]: micromechanics in the sense that transverse microcracking and delamination are described through discrete cracks; mesomechanics in the sense that fiber/matrix debonding and mesodelamination are represented as damage in the field of continuum mechanics. Our objective is to develop a comprehensive model compatible with both the micro and meso approaches.

The next section reviews the main degradation mechanisms of composites. These mechanisms are divided into two main groups: discrete mechanisms and diffuse mechanisms; this leads naturally to the hybrid nature of the micromodel.

The foundations of the model, i.e. continuum mechanics for diffuse events and finite fracture mechanics for discrete mechanisms, are recalled in Section 3.

In Section 4, we describe our proposed improvement to this original version. Inelastic behavior (viscosity and plasticity) is introduced through continuum mechanics models

characterized by the use of effective quantities.
Finally, after a brief description of the dedicated high-performance numerical strategy, the last section presents different examples showing the capabilities and limits of the model.

2. BASES OF THE COMPUTATIONAL DAMAGE MICROMODEL

2.1 Degradation features on the microscale

We consider the accumulation of degradations to be well-known and described through a few main mechanisms divided into two groups, called diffuse and discrete mechanisms.

Diffuse degradations

The first two mechanisms to occur are matrix/fiber debonding [6] and diffuse delamination. Matrix/fiber debonding is a quasi-homogeneous phenomenon within the ply which leads to natural homogenization on the ply's scale. This happens mainly under shear loading and results in a sharp decrease in shear modulus.
Diffuse delamination is associated with microvoids within the laminar interface.
Both phenomena can occur in the absence of discrete mechanism. The percolation of these diffuse phenomena leads to the classical discrete mechanisms described below.

Discrete degradations

Most experimental observations on the microscale are related to two mechanisms, called transverse microcracking and local delamination.
Transverse microcracking occurs mainly in plies subjected to transverse loading, and spreads throughout the plies' thickness. This has often been studied in the framework of finite fracture mechanics [7]. As the loading increases, overloads appearing at the tips of microcracks lead to local delamination at the interfaces between plies [8],[9],[10]. This leads to microcracking saturation and contributes to the failure of the structure as a result of localization of the degradation. At this point, fiber brekeage can occur.

2.2 Basic featuress of the computational damage micromodel for laminates

The computational damage micromodel for laminates was introduced in [1] and recently improved with the addition of fatigue under mechanical or thermal cycling [11], [12]. The objective is to define what one calls the "virtual material", which can be considered to be a model combining the most important aspects of the composite's behavior under general loading. The introduction of both the micro and meso points of view (in order to create a synergy between these two scales which are widely used in the modeling of composites) makes this description hybrid.
On the microscale, the laminate is described as an assembly of layers, made of fiber/matrix material and interfaces. These interfaces constitute potential cracks (transverse microcracks or local delaminations) (see Figure 1).

The fiber/matrix material is the result of the homogenization of an elementary volume containing fibers and matrix (Figure 2). This material follows the classical continuum mechanics framework, while finite fracture mechanics is used to describe the behavior of the interfaces. It comes that the dimensions of the fiber/matrix material are defined by the sizes of the surrounding interfaces. Energy considerations [13] define a minimum characteristic propagation length, of the order of the ply's thickness, below which a crack becomes unstable. For delamination, this length is of the order of ten percent of the ply's

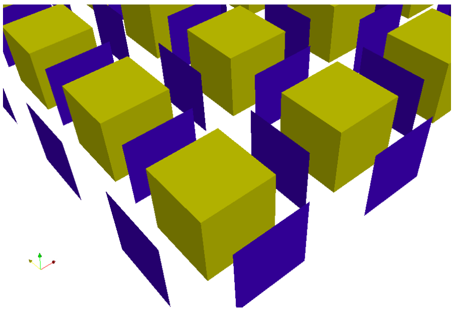

Figure 1: Repartition of fiber/matrix material and interfaces

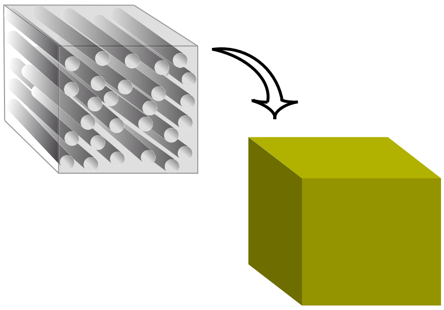

Figure 2: Elementary volume homogenization

thickness. The knowledge of these interfaces is useful from a numerical point of view in the sense that potential cracks are defined *a priori*, which leads to a numerical strategy which can be well-adapted to the model.

The damage mesomodel for diffuse mechanisms

This model, which was first introduced in [4] and [14] and is summarized below, describes the damage associated with fiber/matrix debonding and the existence of small cracks within the matrix which connects neighboring fibers. (Originally, this mesomodel also included microcracking.) This behavior, introduced into the fiber/matrix material model, involves two damage variables (assumed to be constant across the ply's thickness) for the shear ($\tilde{d}$) and transverse ($\tilde{d}'$) directions. Thus, damage is expressed as a function of the damage forces through the following evolution law:

$$\tilde{d} = sup\left[\frac{\sqrt{\tilde{Y}_{\tilde{d}} + b_2\tilde{Y}_{\tilde{d}'}} - \sqrt{Y_0}}{\sqrt{(Y_c)}}\right] \qquad \tilde{d}' = b_3\tilde{d} \tag{1}$$

where b_2, b_3, Y_c and Y_0 are coefficients to be identified experimentally. The damage forces are defined as functions of the stress:

$$\tilde{Y}_{\tilde{d}'} = \left\langle\left\langle \frac{\langle\sigma_{22}\rangle_+^2}{2E_2^0(1-\tilde{d}')} \right\rangle\right\rangle \qquad \tilde{Y}_{\tilde{d}} = \left\langle\left\langle \frac{\sigma_{12}^2}{2G_2^0(1-\tilde{d}')} \right\rangle\right\rangle \tag{2}$$

where $\langle\langle..\rangle\rangle$ denotes the mean value across the thickness, and $\langle..\rangle_+$ the positive part. Remark: effective quantities (particularly the effective stress) are defined as follows:

$$\tilde{\sigma} = \begin{bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ \tilde{\sigma}_{33} \\ \sqrt{2}\tilde{\sigma}_{12} \\ \sqrt{2}\tilde{\sigma}_{13} \\ \sqrt{2}\sigma_{23} \end{bmatrix} = \begin{bmatrix} \sigma_{11} \\ \frac{\langle\sigma_{22}\rangle_+}{(1-\tilde{d}')} + \langle\sigma_{22}\rangle_- \\ \frac{\langle\sigma_{33}\rangle_+}{(1-\tilde{d}')} + \langle\sigma_{33}\rangle_- \\ \sqrt{2}\frac{\sigma_{12}}{(1-\tilde{d})} \\ \sqrt{2}\frac{\sigma_{13}}{(1-\tilde{d})} \\ \sqrt{2}\frac{\sigma_{23}}{(1-\tilde{d}_{23})} \end{bmatrix} \tag{3}$$

The probability of occurrence of microcracking increases with an increase of diffuse damage. When the loading is high enough, microcracking (followed by delamination) is activated naturally and is governed by finite fracture mechanics as described below.

Finite fracture mechanics for cracking

There are two types of surfaces, associated respectively with transverse microcracks and local delamination. In both cases, the failure criterion is based on discrete energy release rates. Each mode's critical energy release rate for the ply is denoted $\{G_c^{I,II,III}\}$. For the calculation of damage forces, initiation is distinguished from propagation. For initiation, the damage force $\{G_{init}^{I,II,III}\}$ is:

$$\{G_{init}^{I,II,III}\} = min\left[h \cdot \frac{\Delta G^{I,II,III}}{h}; \bar{h} \cdot \frac{\Delta G^{I,II,III}}{h}\right] \tag{4}$$

where h is the ply's thickness and $\bar{h}$ a critical thickness of the order of twice that of the elementary material ply. ΔG is the discrete energy release rate associated with the rupture of the interface. When the crack propagates, we define:

$$\{G_{propa}^{I,II,III}\} = \{\Delta G^{I,II,III}\} \tag{5}$$

Then, the cracking criterion is defined according to the classical micromechanical evolution law:

$$\left[\left[\frac{G_{init/propa}^{I}}{G_c^{I}}\right]^{\alpha} + \left[\frac{G_{init/propa}^{II}}{G_c^{II}}\right]^{\alpha} + \left[\frac{G_{init/propa}^{III}}{G_c^{III}}\right]^{\alpha}\right]^{1/\alpha} \geq 1 \tag{6}$$

When this criterion is reached, the surface becomes fully cracked and a unilateral contact condition with friction is applied.
The failure criterion for delamination is based on the same idea, except that fiber breakage is defined within a minimum fracture volume made of fiber/matrix material [13].

3. IMPROVEMENT OF THE MICROMODEL

3.1 Introduction of plasticity

The plastic behavior chosen is based on a transverse isotropic threshold f which is a function of the effective stress:

$$f(\tilde{\sigma}, p) = \sqrt{\tilde{\sigma}_{12}^2 + \tilde{\sigma}_{13}^2 + \tilde{\sigma}_{23}^2 + a(\tilde{\sigma}_{22}^2 + \tilde{\sigma}_{33}^2)} - R(p) - R_0 \tag{7}$$

Isotropic hardening, described by a classic power law, is assumed:

$$R(p) = \beta p^{\alpha} \tag{8}$$

where β and α are material constants. The plastic behavior follows the classical evolution:

$$f(\tilde{\sigma}, p) < 0 \quad \dot{p} = 0 \tag{9}$$
$$f(\tilde{\sigma}, p) = 0 \quad \text{and} \quad \dot{f}(\tilde{\sigma}, p) < 0 \quad \dot{p} = 0 \tag{10}$$
$$f(\tilde{\sigma}, p) = 0 \quad \text{and} \quad \dot{f}(\tilde{\sigma}, p) > 0 \quad \dot{p} > 0 \tag{11}$$

3.2 Introduction of Viscosity

Many authors describe the time-dependent response of composites through viscoelasticity or viscoplasticity. Our viscosity model is based on Schapery's well-known model [15], which is often used in the field of composites [16],[17]. In the shear direction, the constitutive nonlinear equation of the viscous part is:

$$\varepsilon_{12}^{v}(t) = g_1 \int_0^t \Delta D(\psi(t) - \psi(\tau)) \frac{d(g_2\sigma_{12})}{d\tau} d\tau \quad \text{with} \quad \psi(t) = \int_0^t \frac{dt'}{a_1} \tag{12}$$

where $\varepsilon_{12}^{v}(t)$ is the viscous strain in the shear direction. $\psi(t)$ is what one calls the reduced time, which enables time/temperature equivalences [18],[19]. $\Delta D(t)$ is the material's time-dependent compliance, identified by creep/recovery experiments and expressed as a Prony series:

$$\Delta D(t) = \sum_i A_i \left(1 - e^{(-t/\lambda_i)}\right) \tag{13}$$

where the material coefficients A_i are identified experimentally. The coefficients g_i are nonlinear and represent the dependence of the viscosity on the stress level, the temperature and the hydrometry. We chose to replace these coefficients by the introduction of an effective stress and an effective strain. The above relation becomes:

$$\tilde{\varepsilon}_{12}^{v}(t) = \int_0^t \Delta D(\psi(t) - \psi(\tau)) \frac{d\tilde{\sigma}_{12}}{d\tau} d\tau \tag{14}$$

In this case, the nonlinearity with respect to the stress level is included through the effective stress, which contains information about damage. Figure 3 shows the results of simulations of simple creep at different stress levels compared to experiments. One can observe that the use of effective quantities make the laws dependent on the stress level and leads to good agreement with the experimental results.

From a global point of view, the use of effective quantities for the plastic and viscous

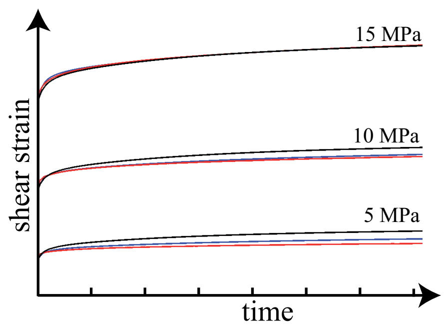

Figure 3: Comparison of the experiment (red), Schapery's linear model (black) and our model which includes the effective stress (blue)

models enables complex behavior to be described with a minimum number of material constants, which reduces the number of experiments necessary to identify the material coefficients. This is what makes the description of most nonlinearities (with respect to stress level, temperature, hydrometry...) through a small number of variables, such as damage, very advantageous. Thus, using effective quantities, the nonlinearity of the different types of behavior is taken into account automatically.

4. THE NUMERICAL SIMULATION

4.1 The computational strategy

The strategy presented here is specific of the particularities of the model and consists of three main steps:
First, the domain is partitioned into subdomains. The choice of these meshed substructures is obvious: each stands for an elementary volume of fiber/matrix material. Thus, the interfaces between these substructures are defined naturally (see Figure 4).
Second, the interface variables (displacements and forces) are divided into micro and macro parts. This separation makes the strategy highly multiscale, which leads to good numerical efficiency.
Finally, the problem is solved using an iterative method, inspired by a more general nonincremental method, called LATIN [20], which was developed in particular at LMT-Cachan.
Each substructure is meshed, and plastic, viscous and damage behavior is introduced. Each associated variable (plastic strain, viscous strain and damage variable) is assumed to be constant within each substructure.
The implementation of the plastic, viscous and damage behavior uses a Newton algorithm (Figure 5). The crack initiation/propagation behavior is introduced by seeking potential cracks at every interface using the energy release rate criterion described above. This

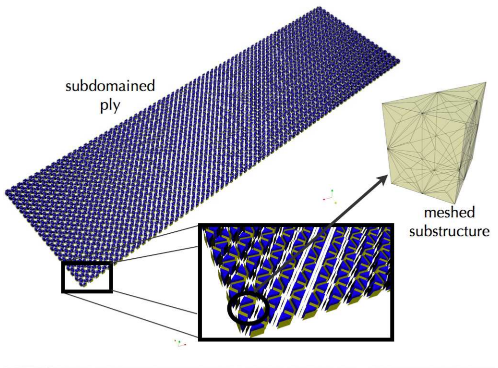

Figure 4: Illustration of the decomposition of a $[\pm 45]_s$ ply;

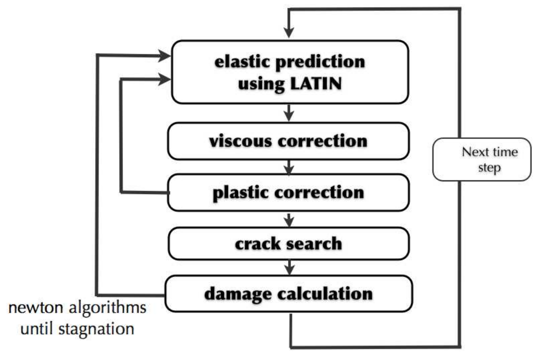

Figure 5: The numerical strategy

numerical treatment lends itself to the resolution of problems with millions of degrees of freedom. Even though the code has not been fully optimized yet, it is already possible to give some illustrations of its numerical possibilities.
Important remark: The purpose of the model developed in this paper is not to simulate industrial structures such as aircraft components. Because of the huge number of degrees of freedom required (e.g. two million for a 21x6x0.6mm laminated composite plate), the dimensions of the numerical examples must remain small. The numerical illustrations are here only to demonstrate the capabilities of the model by comparing its results with experiments. This model will serve as a basis for other models which are more efficient numerically, such as the micromechanics-based improved damage mesomodel proposed in [21].

4.2 Illustrations

In the following examples, we tried to simulate the behavior of a 21mm-long, 6mm-wide rectangle of carbon/epoxy composite made of T700/M21. The thickness of the elementary ply is 0.3mm. The material's main coefficients are given in Table 1.

E_1= 120 GPa	E_2=E_3= 8.9 GPa	G_{12}=G_{13}=5.3 GPa	G_{23}=5 GPa
ν_{12}=ν_{13}=0.3	ν_{23}= 0.35	Y_0=0.049 MPa	Y_c=6.8 MPa
b_2=0	G_c^I=250 Jm^{-2}	G_c^{II}= 0.25 Jm^{-2}	G_c^{III}= 0.25 Jm^{-2}

Table 1: Material properties

[+45/-45]$_s$ laminates

This part concerns the simulation of a [+45/-45]$_s$ sequence, which has the particularity of reaching high levels of diffuse damage and viscosity. The composite is successively loaded, then unloaded, at increasing stress levels. Figures 6 and 7 show the response of the laminate in terms of damage, plasticity and viscosity. Figure 10 shows the damage map over the geometry.

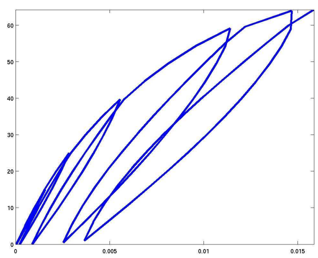

Figure 6: Evolution of stress toward strain

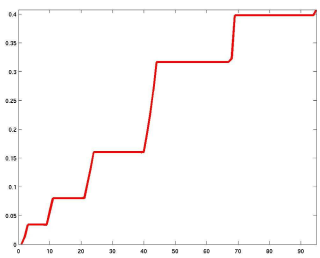

Figure 7: Evolution of the shear damage

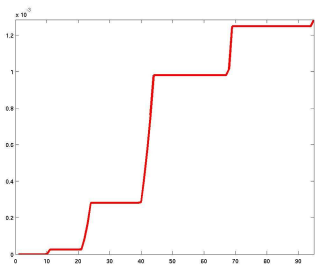

Figure 8: Evolution of the plastic strain

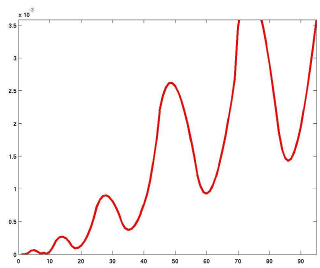

Figure 9: Evolution of the viscous strain

5. CONCLUSIONS

The computational damage micromodel described in this paper along with recent improvements leads to a comprehensive hybrid model capable of describing numerous types of behavior often encountered in composites, such as diffuse and discrete damage mechanisms, plasticity, viscosity, or thermomechanical fatigue. Cracks are represented explicitly, whereas the other types of behavior are homogenized. The association of this

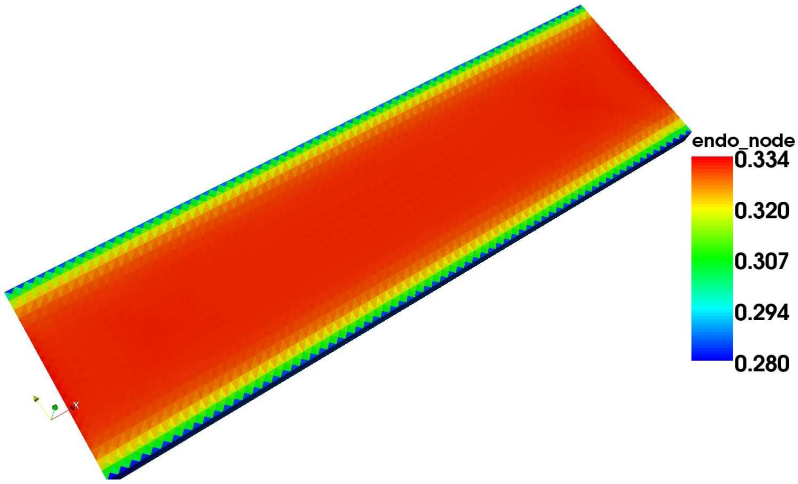

Figure 10: Shear damage map

model with a high-performance numerical strategy enables one to simulate experiments and show that the results are in good agreement with the experimental observations. Such a model is capable of improving the description of the localization of degradations until the complete failure of the composite. The numerical aspects need to be optimized before undertaking the simulation of more complex geometries. At the present time, the model should be used as a virtual material, i.e. as a material data base.

REFERENCES

[1] Ladevèze P., “Multiscale computational damage modelling of laminate composites”, *Taljera-Manson editor, Course CISM*, 2005.

[2] Dvorak G.J. and Laws N., “Analysis of progressive matrix cracking in composite laminates. Part 2: First ply failure”, *Journal of Composite Materials*, 1987;21:309-329.

[3] Berthelot J.M., “Transverse cracking and delamination in cross-ply glass-fiber and carbon-fiber reinforced plastic laminates: static and fatigue loading”, *Applied Mechanics Reviews*, 2003;56(1):1-37.

[4] Ladevèze P., “ Sur la mécanique de l’endommagement des composites”, *Comptes-rendus de JNC5 (edited by C. Bathias ans D. Menkès), in french*, 1986;667-683.

[5] Ladevèze P. , Allix O., Deu J.F. and Lévèque D., “A mesomodel for localization and damage computation in laminates”, *Computer Methods in Applied Mechanics and Engineering*, 2000;183:105-122.

[6] Lagattu F. and Lafarie-Frénot M.C., “Variation of PEEK matrix crystallinity in APC-2 composite subjected to large shearing deformation”, *Composite Science and Technology*, 2000;60:605-612.

[7] Nairn J.A., “Matrix microcracking in composites”, *Taljere-Manson editor, Polymer Matrix Composites,Vol. 2 of Comprehensive Composite Materials, Elsevier Science*, 2000;Chap.13:;403-432.

[8] Nairn J.A. and Hu S., “The initiation and growth of delaminations induced by matrix microcracks in laminated composites”, *International Journal of Fracture*, 1992;57:1-24.

[9] Ogihara S. and Takeda N., “Interaction between transverse cracks and delamination during damage process in CFRP cross-ply laminates”, *Composites Science and Technology*, 1995;54(4):395-404.

[10] Zhang J., Fan J., and Herrmann K.P., “Delaminations induced by constrained transverse cracking in symetric composite laminates”, *International Journal of Solids and Structures*, 1999; 36:813 -846.

[11] Lubineau G., P. Ladevèze P. and Violeau D., “Durability of CFRP laminates under thermomechanical loading: A micro-meso damage model”, *Composites Science and Technology*, 2006;66(7/8):983-992.

[12] Lubineau G., Violeau D. and P. Ladevèze P., “Illustrations of a microdamage model for laminates under oxidizing thermal cycling”, *Composites Science and Technology*, 2007;doi:10.1016/j.compositech.2007.10.042.

[13] Ladevèze P., Lubineau G. and Violeau D., “A computational damage micromodel of laminated composites”, *International Journal of Fracture*, 2006;137:139-150.

[14] Ladevèze P., “About a damage mechanics approach”, *Mechanics and Mechanisms of Damage in Composite and Multimaterials, MEP, a D. Baptiste Edition*, 1989;119-142.

[15] Schapery R.A., “A theory of nonlinear thermoviscoelasticity based on irreversible thermodynamics”, *Proceeding of the Fifth US National Congress in Applied Mechanics, ASME*, 1966;511.

[16] Papanicolaou G.C., Zaoutos S.P. and Cardon A.H., “Prediction of the non-linear viscoelastic response of unidirectional fiber composites”, *Composites Science and Technology*, 1999;59:1311-1319.

[17] Howard M. and Hollaway L., “The characterization of the nonlinear viscoelastic properties of a randomly orentated fibre/matrix”, composite *Composites*, 1987;18(4):317-323.

[18] Goertzen W.K. and Kessler M.R., “Creep behavior of carbon firber/epoxy matrix composites”, *Materials Science and Engineering*, 2006;421:217-225.

[19] Nevière R., “An extension of the time-temperature superposition principle to non-linear viscoelstic solids”, *International Journal of Solids and Structures*, 2006;43:5295-5306.

[20] Ladevèze P., Nouy A., “On a computational strategy with time and space homogenization for structural mechanics”, *Computer Methods in Applied Mechanics and Engineering*, 2003;192:3061-3087.

[21] Lubineau G., Ladevèze P., “Construction of a micromechanics-based intralaminar mesomodel, and illustrations in ABAQUS/Standard”, *Computational Materials Science*, 2007;doi:10.1016/j.comatsci.2007.07.050.