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Christian Hochard, Pierre-Antoine Aubourg, Jean-Paul Charles. Modelling of the mechanical behaviour of woven-fabric CFRP laminates up to rupture. *Composites Science and Technology*, 2001, 61 (2), pp.221-230. <10.1016/S0266-3538(00)00199-8>. <hal-00221484>

**HAL Id: hal-00221484**

**<https://hal.science/hal-00221484v1>**

Submitted on 28 Feb 2025

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# Modelling of the mechanical behaviour of woven-fabric CFRP laminates up to failure

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In order to model the mechanical behaviour of woven composite materials up to failure, we have adapted models developed for unidirectional plies and based on damage mechanics. The model used to describe the degradations is non-linear with progressive damage and inelastic strains. The behaviour of woven plies in the warp and fill directions is elastic and brittle. The progressive loss of rigidity (shear modulus) is described by a damage variable, the development of which depends on the shear load but also on the in-plane tension load. The inelastic strains concern only shear strains. The identification of the model was done by means of two tensile tests. A program that makes it possible to simulate the woven laminate behaviour was carried out. Validation tests, which compare numerical results and experimental results, have shown the relevance of the model. These tests show a lesser sensitivity of woven-ply laminates to delamination phenomena with respect to unidirectional plies. In the case of woven-ply laminates, the only inelastic damageable model of the ply should be sufficient to describe the behaviour of any laminate

*Keywords:* A. Textile composites; B. Mechanical properties; B. Fracture; C. Damage mechanics; C. Laminates

## 1. Introduction

Although they show lower mechanical characteristics than those of unidirectional plies, composite materials with woven reinforcement allow an easier lay-up for complex surfaces. Moreover, their organisation limits the development of intra-laminar macro-cracks. An optimum use of laminates made up of woven plies requires the modelling of their behaviour up to rupture.

Knowing woven-ply characteristics, the classic models used for laminates [1] apply without restriction if the assumption of linear elasticity is valid. The modelling of the progressive degradation of the composite plies within a laminate is a less well-understood problem, as it has to take into account their non-linear damageable behaviour. Much work has been devoted to damageable unidirectional plies but they are much rarer in the case of woven plies. Harry and Massard [2] have described a method based on the use of the Tsai–Wu quadratic criterion. Simple in use, this method, however, requires a

knowledge of the characteristics of a unidirectional ply representative of the warp and fill of the woven fabric considered. It does not allow us to simulate the progressive damage of the woven ply. The periodic geometry of the woven ply has led several authors to use numerical homogenisation by finite elements. Léné and Paumelle [3] thus provided a detailed description of the state of stress in a woven ply. Other authors introduced a progressive rupture [4,5]. In an incremental analytical approach, Naik [6] supplemented the diagram of stiffness reduction of Blacketter [4] by non-linear behaviour of the matrix and a model of the bending and cracking of the yarn. Aussedat et al. [7] introduced the continuum damage mechanics into an analytical method supplemented by a numerical method using the observation of the cracks on the edges of woven-ply coupons. Finally, Gao et al. [8] modelled woven-fabric laminate behaviour under tension loading by a shear-lag analysis.

In the approach suggested here, the authors' objective is to answer industrial needs, which require us to take into account the behaviour of woven-ply reinforced laminates in structural analysis. This analysis is intended

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for complex structures that must undergo some extreme loads with a high degree of reliability. To that purpose it is necessary, on the one hand, to limit the number of calculation stages (each one being linked to a simplifying assumption) and, on the other hand, to base the modelling on simple characterisation tests usually carried out in the industrial laboratory at a limited cost. Finally our model has to be as simple as possible in order to maintain reasonable calculating times for structures presenting a great number of degrees of freedom.

In the case of carbon-fibre-reinforced plastic (CFRP) laminates, many damage mechanisms appear: interfacial matrix/fibre debonding, matrix micro-cracks, fibre rupture, transverse cracking and delamination. These mechanisms present unilateral features because of the opening or the closing of the micro-defects. Moreover, in the case of composites with a damageable behaviour, structural effects (stain localisation) often lead to the rupture. Models defined on the micro-scale can not describe all these damage mechanisms and structural effects which appear on different scales. ‘Simplified models’ developed by Ladevèze et al. [9,10,14] for CFRP laminates with unidirectional plies allow a correct description of these various intra- and inter-laminar damage mechanisms at a reasonable cost. These models use damage variables to describe the decreasing of the elastic moduli on the scale of the ply. These ‘meso-scale’ models, the scale of which is adapted to laminate optimisation and characterisation, can be an answer to the previously underlined industrial needs.

In order to describe the behaviour of composites with woven reinforcement, we have adapted the ‘meso-scale’ models quoted above [11,12]. The kinematics of the damage uses only one progressive variable to describe the decreasing of stiffness in shear. The development of this damage variable depends on the shear load but also on the traction load in the directions of warp and fill. A plastic-hardening model describes the inelastic strains observed for a shear load. Three tension tests are necessary to identify the different parameters of the model. We present another approach, based on the analysis of the damageable behaviour of an equivalent [0,90] unidirectional ply laminate, allowing to determine the tension/shear coupling coefficient of the model. Validation tests, which compare numerical results and experimental results, for different laminates are described.

## 2. Damageable behaviour of woven plies

### 2.1. Presentation of the material and experimental observations

This study relates to a carbon/epoxy composite G802/914 (Hexcel-Brochier). The reinforcement is a carbon

fabric of the four-harness satin type, balanced in warp and fill (Fig. 1). The warp and fill consist of 3000 carbon filament yarns (Toray).

In the warp and fill directions, the woven ply shows a brittle linear elastic behaviour in tension (see Fig. 2). The damage following these directions does not influence the behaviour of the ply under traction load. However, traction in the warp direction generates micro-cracks in the matrix within the fill yarns and also within the warp yarns [13]. For a loading in shearing obtained with a tensile test on a  $[45]_8$  laminate, a reduction of both the shear modulus and inelastic strains are observed (see Fig. 3). The decreasing of this modulus is a consequence of the ply shear stress that generates some fibre/matrix decohesion and matrix micro-cracks within warp and fill yarns. The observed inelastic strains and the loading/unloading hysteresis (Fig. 3) are mainly due to the slipping/friction phenomena between the fibres and matrix.

### 2.2. Damage modelling for a woven ply

On the basis of a damage computational approach, models describing the progressive damage until rupture for different composites (CFRP laminates, woven ceramic composites.) have been already proposed and validated by Ladevèze et al. [9,10,14]. In the case of CFRP laminates, the composite is defined at the level of the plies and the interfaces between the plies in order to describe the various intra- and inter-laminar degradations. These ‘meso-scale’ models use a thermodynamic formalism where internal variables are associated with the decreasing of the elastic moduli. The plies are regarded as homogeneous orthotropic. A plastic-hardening model coupled to damage describes the inelastic strains. In the case of unidirectional plies, only the in-plane transversal and shear moduli are modified under the assumption of a progressive damage associated to micro-cracks parallel to the fibres [14].

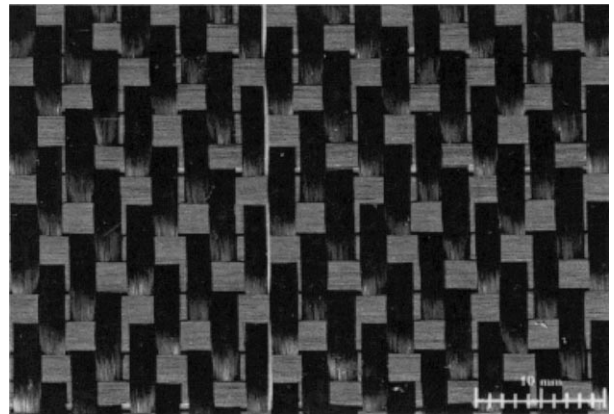


Fig. 1. Woven ply of four harness satin type, balanced in warp and fill.

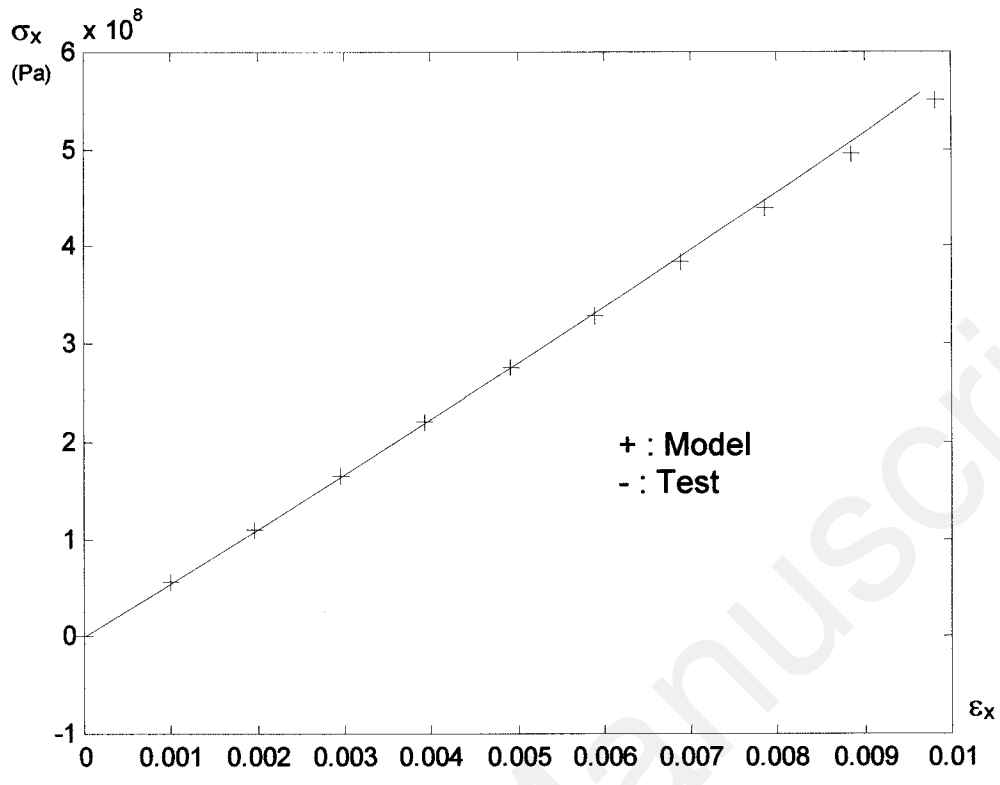


Fig. 2. Evolution of the stress according to the strain for a tensile test on  $[0]_8$  laminate.

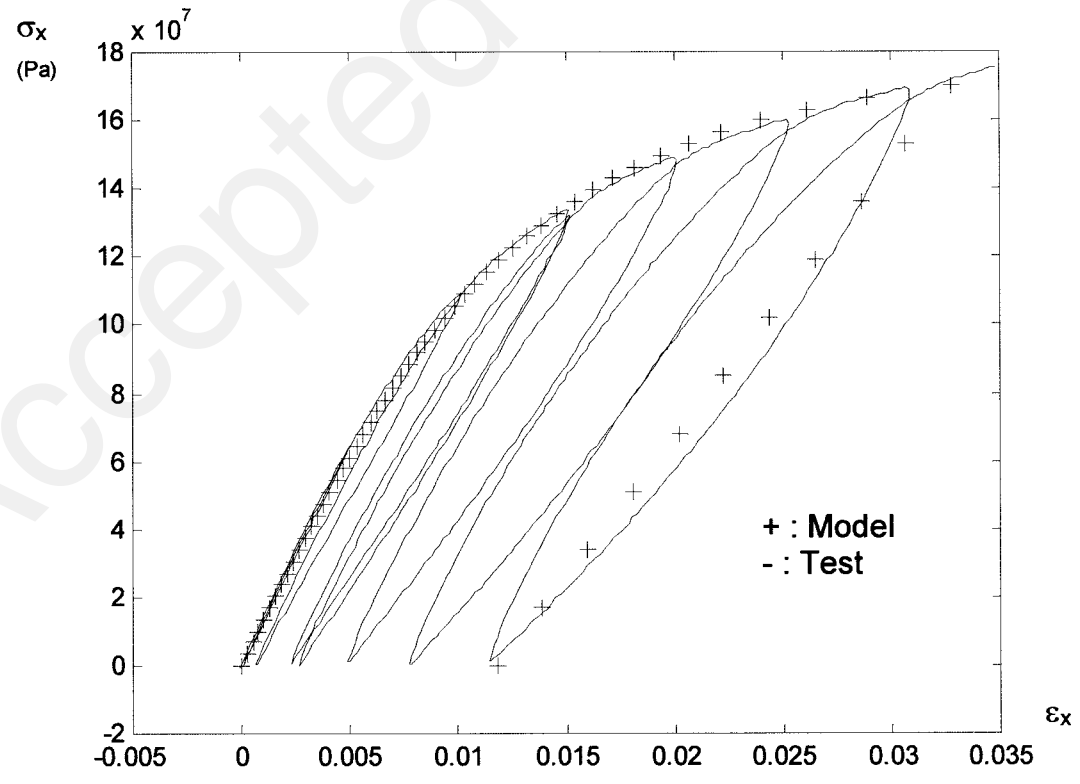


Fig. 3. Evolution of the stress according to the strain for a tensile test on a  $[45]_8$  laminate.

To model the behaviour of the CFRP laminates with woven reinforcement, we have adapted this ‘meso-scale’ model defined for unidirectional plies. The model is written for balanced or non-balanced in warp and fill woven plies. The chosen damage kinematics uses three internal variables for damage ( $d_1$ ,  $d_2$ ,  $d_{12}$ ) which are related, respectively, to the brittle fracture of fibres in the warp direction, the fill direction and the decreasing of stiffness in shear. The development of the progressive damage  $d_{12}$  depends on the shear load but also on the traction load which generates micro-cracks within the fill and warp. These micro-cracks are mainly located at the fibre/matrix interfaces and therefore are supposed to be parallel to the fill and warp directions. Under the assumption of plane stresses and small perturbations, we can write the strain energy of the woven ply in the following form:

$$E_D^{ps} = \frac{1}{2} \left[ \frac{\langle \sigma_1 \rangle_+^2}{E_1^0(1-d_1)} + \frac{\langle \sigma_1 \rangle_-^2}{E_1^0} - 2 \frac{v_{12}^0}{E_1^0} \sigma_1 \sigma_2 + \frac{\langle \sigma_2 \rangle_+^2}{E_2^0(1-d_2)} + \frac{\langle \sigma_2 \rangle_-^2}{E_2^0} + \frac{\sigma_{12}^2}{G_{12}^0(1-d_{12})} \right] \quad (1)$$

where  $\langle . \rangle_+$  is the positive part. The tension energy and compression energy are split in order to describe the unilateral feature due to the opening and closing of the micro-defects. From this potential, thermodynamic forces associated with the tension and shear internal variables  $d_i$  ( $i=1$  and  $2$ ) and  $d_{12}$  are defined:

$$Y_{d_i} = \frac{\partial E_D^{ps}}{\partial d_i} = \frac{\langle \sigma_i \rangle_+^2}{2E_i^0(1-d_i)^2} \quad (2)$$

$$Y_{d_{12}} = \frac{\partial E_D^{ps}}{\partial d_{12}} = \frac{\sigma_{12}^2}{2G_{12}^0(1-d_{12})^2}$$

The development of the internal variables depends on these thermodynamic forces, and more precisely on their maximum values during the history of the loading.

In traction, the development of  $d_1$  and  $d_2$  is brutal in order to represent the brittle behaviours according to the warp and the fill directions. To take into account the traction/shear coupling during the development of  $d_{12}$ , we define the equivalent thermodynamic force and the maximum value of this force during the history of the loading:

$$Y = \alpha_1 Y_{d_1} + \alpha_2 Y_{d_2} + Y_{d_{12}} \quad \text{and} \quad \underline{Y}(t) = \sup_{\tau \leq t} (Y(\tau)) \quad (3)$$

where  $\alpha_1$  and  $\alpha_2$  are the tension/shear coupling constants. It should be noted that this equivalent force

which govern the development of the progressive damage variable  $d_{12}$  does not depend on the compression stresses in the warp and fill directions. As for the unidirectional plies [9], a linear law with respect to the square root of  $\underline{Y}$  is chosen to describe the damage variable development:

$$d_{12} = \left\langle \frac{\sqrt{\underline{Y}} - \sqrt{Y_0}}{\sqrt{Y_c} - \sqrt{Y_0}} \right\rangle_+, \quad d_1 = 0 \quad \text{and} \quad d_2 = 0 \quad \text{if} \quad (4)$$

$$d_{12} < 1 \quad \text{and} \quad Y_{d1} < Y_{1f} \quad \text{and} \quad Y_{d2} < Y_{2f}$$

else if  $d_{12} = d_1 = d_2 = 1$

where the constant parameters  $Y_0$  and  $Y_c$  correspond to the threshold and the critical value of the development of  $d_{12}$  (which varies from 0 to 1).  $Y_{1f}$  and  $Y_{2f}$  are the parameters, which define the ultimate forces in the warp and fill directions. As we shall see in the next section on the comparison between the model and the tests, this choice for the damage development law is satisfactory.

### 2.3. Modelling of the inelastic strains

After loading on a laminate [45]<sub>8</sub> (Fig. 3), inelastic strains are observed. These strains can be linked to the slipping/friction phenomena between the fibres and matrix as a consequence of the damage. Because of the warp and fill fibre directions, which prevent traction inelastic strains, only the shear inelastic strains are significant. We shall describe these strains by a plastic-hardening model [14]. The coupling between the damage and plasticity is taken into account by using the effective stress and the effective strain [9], which are defined as:

$$\tilde{\sigma}_{12} \dot{\tilde{\epsilon}}_{12}^p = \sigma_{12} \dot{\epsilon}_{12}^p \quad \text{where} \quad \tilde{\sigma}_{12} = \frac{\sigma_{12}}{(1-d_{12})} \quad \text{and}$$

$$\dot{\tilde{\epsilon}}_{12}^p = \dot{\epsilon}_{12}^p (1-d_{12}) \quad (5)$$

It is assumed that the stresses  $\sigma_1$  and  $\sigma_2$  do not influence the elastic field defined by:

$$f(\tilde{\sigma}_{12}, p) = |\tilde{\sigma}_{12}| - (R(p) + R_0) \quad (6)$$

where  $R_0$  represents the initial threshold for the inelastic strain and  $R(p)$  is the hardening function of the accumulated inelastic strain  $p$  chosen such as:

$$R(p) = K p^\gamma \quad (7)$$

where  $K$  is the power law coefficient and  $\gamma$  is the power law exponent. Then, by requiring the inelastic strain rates to be normal to the elastic domain function, we obtain:

$$\dot{\varepsilon}_{12}^p = \dot{p} \frac{\partial f}{\partial \tilde{\sigma}_{12}} = \dot{p} \frac{\tilde{\sigma}_{12}}{R + R_0} \text{ with } \dot{p} \geq 0 \left( \frac{\tilde{\sigma}_{12}}{R + R_0} = \text{sign}(\tilde{\sigma}_{12}) \right) \quad (8)$$

The yield conditions are then written as:

$$\dot{p} = \begin{cases} \left| \dot{\varepsilon}_{12}^p \right| = \left| \frac{\dot{\tilde{\sigma}}_{12}}{\partial R} \right| & \text{if } f = 0 \text{ and } \dot{f} = 0 \\ \dot{p} = 0 & \text{otherwise} \end{cases} \quad (9)$$

The loading/unloading hysteresis, which is mainly due to the slipping/friction phenomena between the fibres and matrix, is not modelled.

### 3. Identification of the coefficients of the woven-ply model

#### 3.1. Balanced in warp and fill composite

In the case of a balanced in warp and fill woven ply, the coefficients  $\alpha_1$  and  $\alpha_2$  are taken equal to  $\alpha$  and the maximum tension forces  $Y_{1f}$  and  $Y_{2f}$  are taken equal to  $Y_f$  (which depends directly from the ultimate traction stress  $X$ ). The ultimate stress  $X$  is determined by a [0]<sub>8</sub> tensile test. The coefficients of shear damage development law are determined by a tensile test on the [45]<sub>8</sub> laminate for which the plies are loaded mainly in shear. The development of the damage  $d_{12}$  obtained from the [45]<sub>8</sub> experiment (from loading/unloading tests) is compared to the model (Fig. 4). The threshold coefficient  $Y_0$  is taken equal to zero. The first approximation of a linear development is satisfactory. It should be noted the high level of damage ( $d_{12}=0.5$ ) at the rupture point which corresponds to a structural instability. The plasticity parameters are determined by a test on a [45]<sub>8</sub> laminate (Fig. 3). Up to now, the behaviour in compression has not been experimentally studied but, as for the unidirectional ply behaviour, it is assumed to be brittle in the warp and fill directions.

#### 3.2. Approximation of the tension/shear coupling coefficient $\alpha$ for a balanced in warp and fill

The coefficient of tension/shear coupling  $\alpha$  can be determined by a test on the [0]<sub>n</sub> laminate subjected to a multiple loading path.

At first approximation, it is also possible to determine  $\alpha$  from the study of a [0/90] laminate made up of unidirectional plies the components of which are similar to the components of the woven plies studied [11]. In order to apply this approximation, we consider the model described in [14,15]. The part of this unidirectional ply

model [14] necessary to show the simplified approach is first recalled. For this model, the shear damage  $d_{12}$  development depends on the transverse stress through the associated equivalent force:

$$Y = bY_{d_2} + Y_{d_{12}} \quad (10)$$

where the coefficient  $b$  defines the tension/shear coupling,  $Y_{d_{12}}$  and  $Y_{d_2}$  are the forces associated respectively to the shear damage and transverse damage  $d_2$ . The development of the shear damage is then defined as:

$$d_{12} = \frac{\sqrt{Y}}{\sqrt{Y_c^{ud}}} \quad (11)$$

where  $Y_c^{ud}$  is the critical value for the unidirectional ply (the threshold is taken equal to zero). In the case of a [0,90] unidirectional ply laminate in traction (with a generalised stress  $\sigma$ ), it is possible to determine the associated forces and the shear damage in each ply from the transverse stresses in each ply. By using the laminate theory and by considering that  $E_2^0 \ll E_1^0$ ,  $\nu_{12}^0 \nu_{21}^0 \ll 1$  and the transverse strain is very small with respect to the longitudinal strain ( $\varepsilon_1 \ll \varepsilon_l$ ), the transverse stresses in the 90° ply and in the 0° ply are:

$$\begin{aligned} \sigma_{22}^{90^\circ} &= E_2^0(1 - d_2^{90^\circ})\varepsilon_l = E_2^0(1 - d_2^{90^\circ}) \frac{2\sigma}{E_1^0} \text{ and} \\ \sigma_{22}^{0^\circ} &= E_2^0(1 - d_2^{0^\circ})\nu_{12}^0 \frac{2\sigma}{E_1^0} \end{aligned} \quad (12)$$

where  $E_1^0$ ,  $E_2^0$  and  $G_{12}^0$  are, respectively, the longitudinal, transverse and initial shear moduli and  $\nu_{12}^0$  the Poisson's ration coefficient of the equivalent unidirectional ply. From these stresses, the associated forces are calculated:

$$\begin{aligned} Y_{d_2}^{90^\circ} &= \frac{(\sigma_{22}^{90^\circ})_+^2}{2E_2^0(1 - d_2^{90^\circ})^2} = E_2^0 2 \left( \frac{\sigma}{E_1^0} \right)^2 \text{ and} \\ Y_{d_2}^{0^\circ} &= \frac{(\sigma_{22}^{0^\circ})_+^2}{2E_2^0(1 - d_2^{0^\circ})^2} = E_2^0 2 \left( \nu_{12}^0 \frac{\sigma}{E_1^0} \right)^2 \end{aligned} \quad (13)$$

and the shear damage in each ply is:

$$\begin{aligned} d_{12}^{90^\circ} &= \frac{\sqrt{bY_{d_2}^{90^\circ}}}{\sqrt{Y_c^{ud}}} = \frac{\sqrt{2bE_2^0}}{E_1^0 \sqrt{Y_c^{ud}}} \sigma \text{ and} \\ d_{12}^{0^\circ} &= \frac{\sqrt{bY_{d_2}^{0^\circ}}}{\sqrt{Y_c^{ud}}} = \nu_{12}^0 \frac{\sqrt{2bE_2^0}}{E_1^0 \sqrt{Y_c^{ud}}} \sigma = \nu_{12}^0 d_{12}^{90^\circ} \end{aligned} \quad (14)$$

and finally the average shear damage over the laminate is:

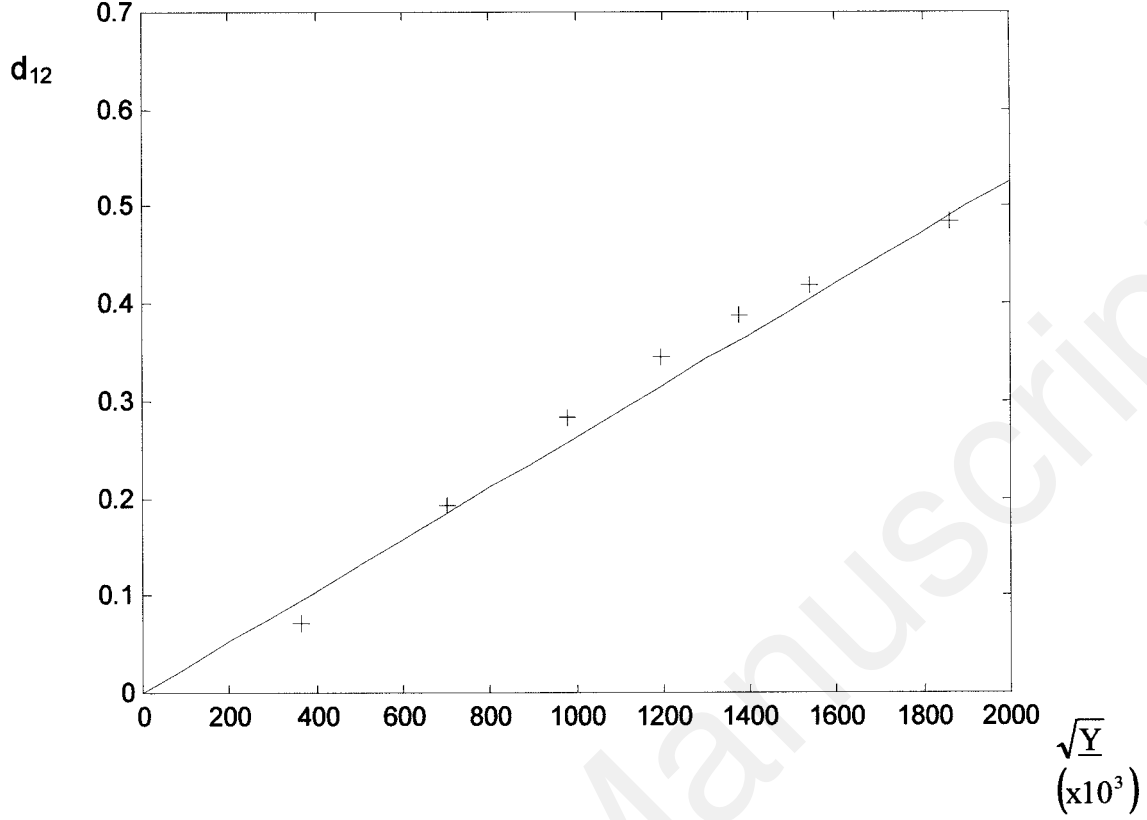


Fig. 4. Evolution of the damage  $d_{12}$  according to the thermodynamic associated forces.

$$d_{12}^{\text{lam}} = \frac{d_{12}^{0^\circ} + d_{12}^{90^\circ}}{2} = \frac{(1 + \nu_{12}^o)}{2} \frac{\sqrt{2bE_2^o}}{E_1^o \sqrt{Y_c^{\text{ud}}}} \sigma \quad (15)$$

$$\alpha = \frac{(1 + \nu_{12})^2 (E_2^o)^2}{2 G_{12}^o E_1^o} \quad (18)$$

In the case of the woven ply (balanced in warp and fill) in traction, it is possible to determine the equivalent associated force and the shear damage from (3) and (4):

$$d_{12} = \frac{\sqrt{\alpha}}{\sqrt{2E_1 Y_c}} \sigma \quad (16)$$

The equality of the woven ply damage (16) and the [0,90] laminate's average damage (15) leads to the expression of the coupling coefficient (with the approximation  $E_1 = E_1^o/2$ ):

$$\alpha = \frac{(1 + \nu_{12})^2}{2} b \frac{E_2^o Y_c}{E_1^o Y_c^{\text{ud}}} \quad (17)$$

By using a micro-mechanical approach, Ledantec [15] showed that the coefficient  $b$  can be taken equal to the ratio  $E_2^o/G_{12}^o$  where  $G_{12}^o$  is the initial shear modulus of the unidirectional ply. By making the assumption of the same shear critical values for the unidirectional ply and the woven ply ( $Y_c = Y_c^{\text{ud}}$ ), the coupling coefficient can be written:

This last assumption ( $Y_c = Y_c^{\text{ud}}$ ) is valid for the unidirectional ply that we studied [16] and then (18) leads to  $\alpha = 0.16$ . This value has to be confirmed by a multi-load test. A possible test is traction in the  $0^\circ$  direction on a large plate and then traction in the  $45^\circ$  direction on a specimen cut from the pre-damaged large plate. A simulation, carried out with the program presented in the next section, of a bi-traction test on a  $[0]_n$  laminate shows that the level of the induced shear damage can be high ( $d_{12} = 0.25$ ) before rupture.

A summary of the elastic properties, damage parameters and inelastic parameters for the woven ply composite G802/914 is given Table 1.

#### 4. Behaviour of woven plies laminates up to rupture

##### 4.1. Assumptions and progressive degradation for the laminate

The damage model previously defined is able to predict the failure of the laminate at the individual layer level (fibre failure, maximum shear damage) or by

Table 1  
Summary of elastic properties, damages parameters and inelastic parameters for the woven-ply composite G802/914

Models parameters	Property–identification test	Value
$E_1, E_2$ (GPa)	Fill and yarn directions Young moduli — $[0]_8$	56
$\nu_{12}$	Poisson’s ratio — $[0]_8$	0.035
$X$ (MPa)	Ultimate fibre direction stress — $[0]_8$	554
$G_{12}$ (GPa)	Initial shear modulus — $[45]_8$	3.8
$Y_c$ (MPa)	Critical shear damage parameter — $[45]_8$	16
$\alpha$	Tens./shear coupling — estimation from equivalent $[0.90]$ UD lam.	0.16
$K$ (MPa)	Inelasticity power law coefficient — $[45]_8$	600
$\gamma$	Inelasticity power law exponent — $[45]_8$	0.39
$R_0$ (MPa)	Hardening function threshold — $[45]_8$	30

instability of the laminate’s response (increment of applied generalised stress is zero when the increment of strain is nonzero). A computer program (WovLam) to simulate the behaviour of any laminate with woven plies at a point of a structure has been developed [11]. This code also makes it possible to simulate the behaviour of laminates made off unidirectional plies [16]. An incremental method is used to determine the stresses, strains and damage in each ply for the complete load history. Generalised strains or stresses can be prescribed, according to the assumptions of Love–Kirchhoff.

#### 4.2. Comparison with the experimental results

The WovLam program makes it possible to analyse coupons subjected to a uniform loading. It was used for a first validation of the previously described modelling. The samples were obtained from plates made in an autoclave with a curing cycle of 1 h at 80°C, followed by 2 h at 180°C under a pressure of 4 bars. The plates were then cut out and machined in order to obtain a reduced section in the central part of the specimen. This choice of geometry made it possible to rule out the occurrence of edge effects at the level of the tabs.

The first two following results on  $[0]_8$  and  $[45]_8$  show the correlation for the laminates that were used for identification of the model parameters. The next laminates  $[67.5]_8$ ,  $[-20, +20]_{2s}$ ,  $[-10, +10]_{2s}$ ,  $[0,45]_{2s}$  and  $[+45, -45, 0, 90]_8$  provide validations of the model.

##### 4.2.1. Parameter identification laminates

Fig. 2 shows the good correlation between theory and experiment for  $[0]_8$ . Fig. 3 shows the correlation for cyclic loading/unloading response of a  $[45]_8$  laminate. This figure demonstrates the relevance of the damage model in that it is able to accurately predict both modulus degradation and inelastic strains up to rupture. In the case of the  $[45]_8$  laminate, the rupture of the laminate corresponds to an instability.

##### 4.2.2. Model validation laminates

Fig. 5 shows the correlation between theory and experiment for the axial response of a  $[67.5]_8$  cyclic ten-

sion. The correlation is excellent for both modulus degradation and inelastic strains. The comparison between theory and experiment for the axial response of a quasi-isotropic  $[0,45]_{2s}$  is very similar to that shown in Fig. 1 and the correlation is very good for the axial strains and failure prediction. The ultimate strain of the  $[0,45]_{2s}$  is very near to the ultimate strain of the  $[0]_8$ .

Fig. 6 shows the correlation between theory and experiment for the axial response of a  $[+20, -20]_{2s}$  tension. As indicated in the figure, the correlation for the axial strain and failure prediction is very good. Failure was predicted to be caused by fibre failure. The comparison and the correlation between theory and experiment for the axial response of a  $[+10, -10]_{2s}$  tension are very similar to that obtained for the  $[+20, -20]_{2s}$  laminate. It should be noted that the model of the woven ply is sufficient to describe the rupture of the  $[-\theta, +\theta]_{ns}$  laminates for small  $\theta$  values.

#### 4.3. Delamination

In the case of a traction on  $[-\theta, +\theta]_{ns}$  laminates with small  $\theta$  values made of unidirectional plies, the model of the ply can not predict the rupture of the laminate [14,15]. This rupture is linked to delamination phenomena, which are three-dimensional effects and appear on the edges of the specimen. That is not the case for woven ply laminates. This non-delamination sensitivity for the woven ply laminates is mainly a consequence of the fact that a  $[-\theta, +\theta]_{ns}$  woven ply laminate is equivalent to a  $[-\theta, -\theta-90, +\theta, +\theta+90]_{ns}$  unidirectional ply laminate, which is different from a  $[-\theta, +\theta]_{ns}$  unidirectional ply laminate.

Another observation concerned a higher delamination resistance for woven ply laminates. Standard tests of delamination were carried out [double cantilever beam (DCB), edge node flexure (ENF) and mixed mode flexure (MMF)] and confirm this result. Table 2 shows a comparison of the critical energy release rate between laminates made of T300/914 unidirectional ply and G802/914 woven ply. This greater resistance to delamination can be a result of the resin pile located at the interfaces and created by the undulations of the fabric

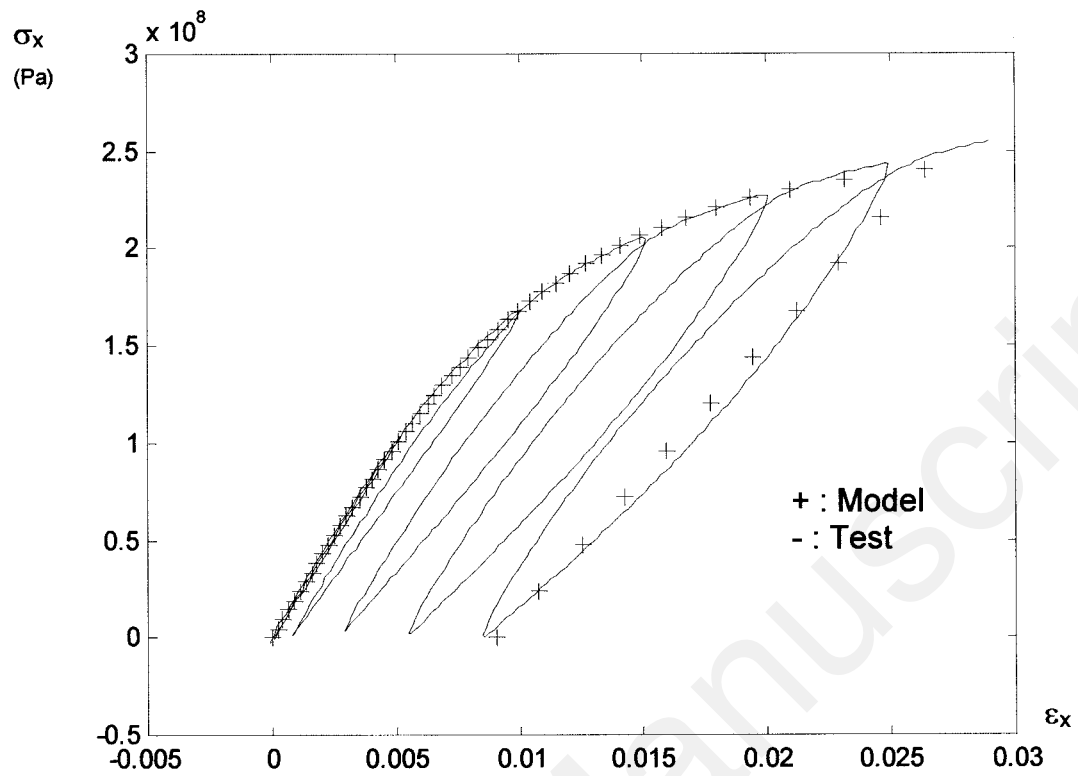


Fig. 5. Evolution of the stress according to the strain for a tensile test on a  $[67.5]_s$  laminate.

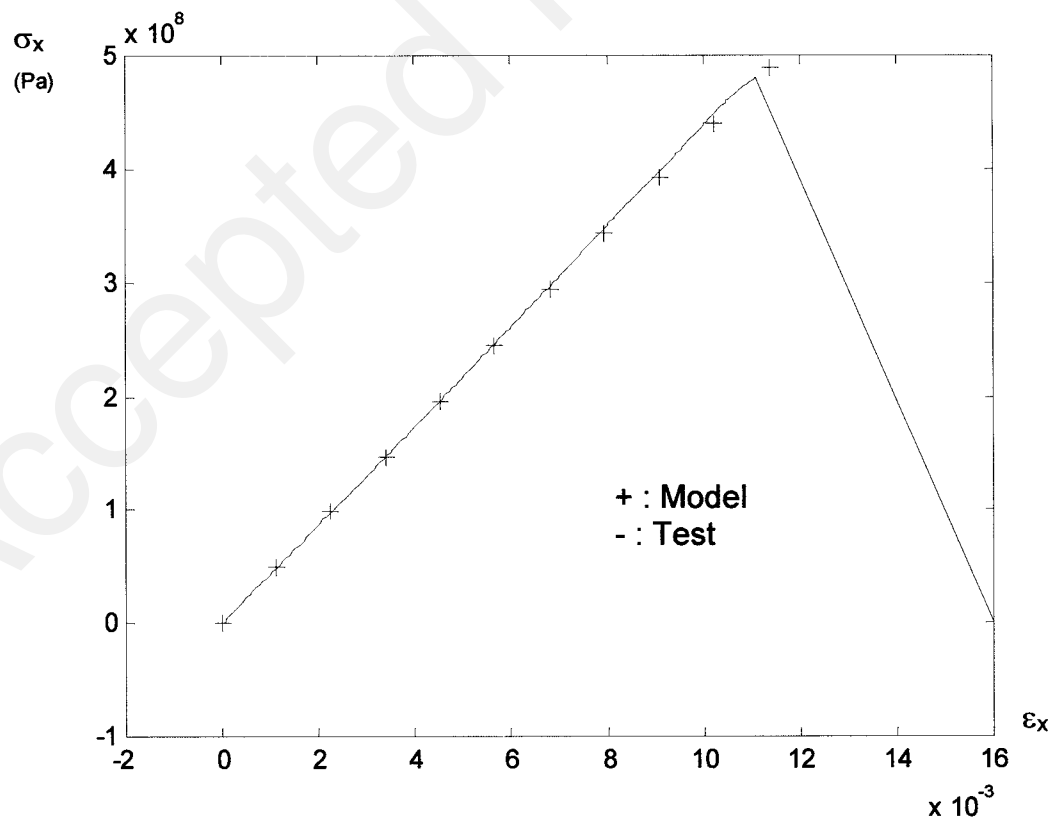


Fig. 6. Evolution of the stress according to the strain for a tensile test on a  $[-20,20]_s$  laminate.

Table 2  
Comparison of the critical energy release rate ( $J/m^2$ ) between T300/914 UD ply and G802/914 woven ply composites

Type of ply (composite)	$G_{cI}$ (DCN test)	$G_{cII}$ (ENF test)	$G_{mixed}$ (MMF test)
Unidirectional ply (T300/914)	180	440	237
Woven ply (G802/914)	400	2000	1130

wicks. Another test on a  $[+45, -45, 0, 90]_{ns}$  woven ply laminate was carried out. The correlation for the axial strain and failure prediction is very good (similar to the  $[0, 45]_{2s}$  laminate). In the case of unidirectional plies, the rupture of this type of laminate is also linked to delamination phenomena and the only model of the ply does not make it possible to predict the rupture.

If this property of low sensitivity to delamination for woven ply is confirmed by further tests, simulations and experimental comparisons of the behaviour until rupture of complex structures are possible. In this case indeed, a simple modelling of the structure by finite elements of shell-type in plane-stress and integrating the inelastic damageable behaviour of the woven ply is sufficient. This relatively simple modelling is not possible in the case of unidirectional plies for which the delamination phenomena linked to 3D effects are dominating in the rupture of the laminate.

## 5. Conclusions

The behaviour until rupture of laminated composites made of unidirectional plies was adapted here to woven plies. A non-linear model was defined and implemented. First validations were carried out and agree well with experimentation. The model obtained uses only one damage variable with progressive development. The characterisation of the model uses standard industrial laboratory tests. The characteristics are obtained directly from these tests without complex calculation. These two points guarantee the maximum of reliability for the prediction of the behaviour of structures up to extreme loads. WovLam allows a post-processing of an elastic finite-element analysis of a complex structure. This post-analysis consists in using the program with the generalised loads on a single point as input data. The validity of this calculation is correct if the ultimate strains are not or very slightly different from those obtained with the elastic behaviour. If the ultimate strains are different from those obtained by the elastic model, the analysis on a point is no longer valid. It is then necessary to extend the post-analysis zone. To that purpose, it becomes necessary to add the modelling suggested for the woven plies to a finite-element program.

While laminates made of unidirectional plies exhibit a high sensibility on delamination phenomena, laminates made of woven plies seem to be less sensitive to these phenomena. In this case, the only inelastic damageable model of the ply is sufficient to describe the behaviour of any laminate and 2D plane-stresses finite-element analysis should allow the computation of complex structures up to rupture.

The model of this study does not depend explicitly on the constitution of the woven ply. If this constitution is changed, new characterisation tests are to be made. Thus, this model is not adapted to parametric studies intended to optimise the constitution of a woven ply. It is thus complementary to micro-mechanical models. The coupling of the model presented here and micro-mechanical models will allow a complete approach, which could satisfy the needs of material design and the requirements of structural analysis.

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Accepted Manuscript