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A progressive first ply failure model for woven ply CFRP laminates under static and fatigue loads

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A non-linear cumulative damage model for woven ply laminates under static and fatigue loads is developed in this paper. The validity scope of this model depends on the 'diffuse damage' phase up to the first intra-laminar macro-crack only (first ply failure model). The model, which is based on a continuum damage approach (CDM) and a non-local fibre rupture criteria, was implemented in a FEM code. Finally, full field strain measurements are used to compare experiments and computations for a plate with an open hole submitted to a fatigue tensile load.

Keywords: Textile composite; Laminate; Fatigue; Damage; Failure

1. Introduction

The design and computation of laminated composite structures in terms of strength is a complex task because many different mechanisms are involved in the damage and rupture to which these materials are subject [1,2]. The principal difficulties in the case of laminated composites relate to the modelling and the simulation of propagations of large cracks in the plies and interfaces (delaminations) under static and fatigue loads [3].

Woven ply are used in helicopter blade due to their good strength and easy lay-up. These structures are submitted to both static and fatigue loadings. Woven ply laminates show good resistance to delamination and are not sensitive to transverse rupture due to weaving [4]. Furthermore, it was observed from experimental tests, at least for static tests, that the rupture of the first ply leads immediately to the rupture of the laminate and the structure. In the case of laminates with woven plies, computations are simpler because it is not necessary to model these large cracks which can appear very early in the case of laminates with

unidirectional (UD) plies. A model based on a continuum damage approach (CDM) was developed for woven ply laminates [4] in the case of static loadings. A first non-linear cumulative damage model in fatigue for UD plies was presented in Ref. [5]. In this model, the development of the damage depends on the maximal static loads and the maximal load over a cycle but it does not take into account the amplitude over the cycle. The model presented in this paper describes the behaviour of woven plies, and takes into account the amplitude as well as the level of damage involved. The validity scope of the model described depends on the 'diffuse damage' phase (which is associated with small cracks) up to the first intra-laminar macro-crack only (first ply failure model). After a loading process has taken place in a laminate, residual strains can be observed. In order to describe them, an isotropic hardening model is used.

The model for woven plies and static loadings was identified on homogeneous tests. In order to validate the model on complex structures, it was implemented in a FEM code [6] and full field strain measurements [7] were used to compare experiments and computations for a plate with an open hole submitted to static tensile loadings [6]. For laminates showing a high level of damage ([45°] for example) the comparison was good but in the case of sequences

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showing brittle behaviour ($[0^\circ]$ for example), the simulations underestimated the rupture. The local criteria generally used to describe the rupture do not work in the case of non-uniform stress field. We proposed a non-local criterion (as Withney and Nuismer in Ref. [8], defined at the level of the laminate in Ref. [9]) defined in this paper at the level of the ply and introducing a characteristic volume depending on the material.

Finally, in order to analyse the different mechanisms that appear in fatigue (evolution of the strain level with respect to the number of cycle, appearance of large cracks), a test on a plate $[45^\circ]$ with an open hole was performed using full field measurement. The fatigue model in shear, identified on homogeneous tests, was implemented in the FEM code and the simulation for the plate with the hole is compared to the experiment in this paper. The material is assumed to be brittle and non-sensitive to the cyclic loading in the direction of the fibres.

2. Woven ply laminates behaviour

Woven ply laminates have weaker mechanical characteristics and are more expensive than UD ply laminates. However, they are used in industry (to make helicopter blade skins, for example). The explanation often given by companies for this choice of woven ply laminates is that they are not subject to transverse rupture, which can be catastrophic in the case of UD plies. Moreover, these materials are more resistant to delamination. The number of damage mechanisms liable to occur is thus reduced and the behaviour of the material is simpler to model up to rupture.

2.1. Damage behaviour of woven plies

The behaviour of this kind of material and the modelling procedure used were previously described in Ref. [4]. The material G963/939 is reinforced with a carbon fabric of the four-harness satin type, with balanced warp and fill yarns (Fig. 1). In the fibre directions, the woven ply shows

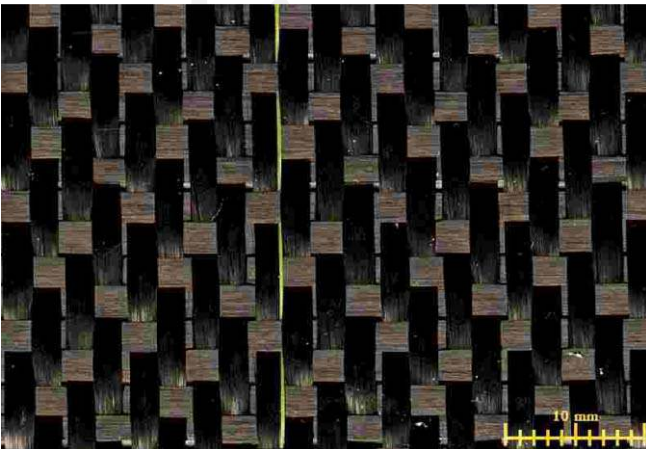


Fig. 1. Woven ply.

a brittle linear elastic behaviour when subjected to tension (see Fig. 2). The damage occurring in these directions does not affect the behaviour of the ply under traction loading. When shear loading is applied (from a tensile test on a $[45]_n$ laminate), a decrease in the shear modulus as well as inelastic strains were observed (see Fig. 3). The decrease in the modulus is due to the ply shear stress, which generates some fibre/matrix decohesion and matrix cracks within the warp and fill yarns. The inelastic strains and the loading-unloading hysteresis observed (Fig. 3) can be due to the slipping/friction processes occurring between the fibres and matrix as the result of the damage.

With a view to modelling the behaviour of laminates with a woven reinforcement, we have adapted the “meso-scale” model developed by Ladeveze for unidirectional plies [10]. This model was designed for dealing with woven plies with balanced or non-balanced warp and fill yarns. The damage kinematics that we have adopted is based on the following three internal damage variables (d_1, d_2, d_{12}): the brittle fracture of fibres in the warp and fill directions and the decreasing stiffness under shear loading, respectively. The gradual development of the damage d_{12} depends on the shear load as well as on the traction load, which generates small cracks in both the fill and the warp components. These small cracks, which are mainly located at the fibre/matrix interfaces, are assumed to run 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:

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

where $\langle \cdot \rangle_+$ is the positive part and $\langle \cdot \rangle_-$ is the negative part. The tension energy and compression energy are split in

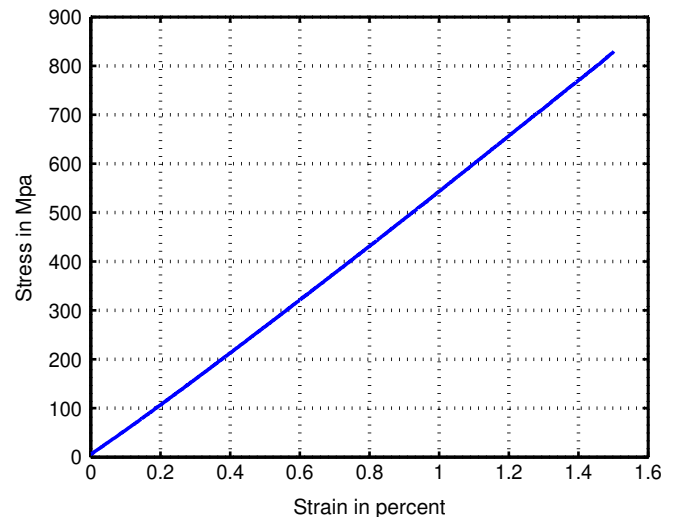


Fig. 2. Fibre direction behaviour.

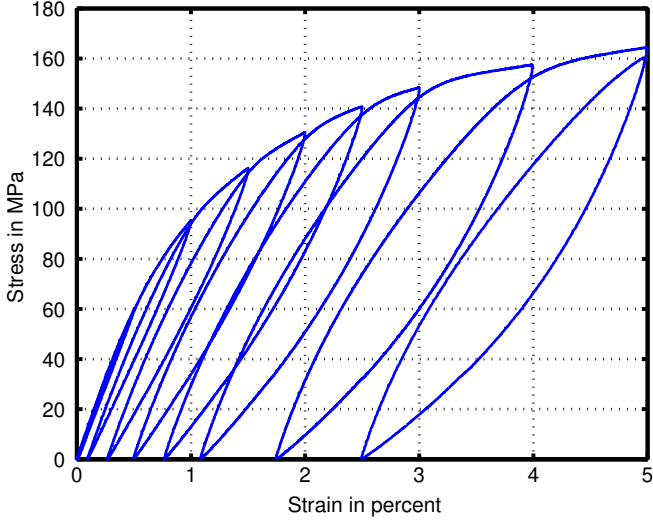


Fig. 3. Shear behaviour.

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

$$Y_{d_i} = \frac{\partial E_D^{ps}}{\partial d_i} = \frac{\langle \sigma_i \rangle_+^2}{2E_i^0(1-d_i)^2}; Y_{d_{12}} = \frac{\partial E_D^{ps}}{\partial d_{12}} = \frac{\sigma_{12}^2}{2G_{12}^0(1-d_{12})^2} \quad (2)$$

The development of the internal variables depends on these thermodynamic forces and more precisely on their maximal value during the history of the loading. In traction, the development of d_1 and d_2 is brutal in order to represent the brittle behaviour in the warp and fill directions. In order to take into account the traction/shear coupling during the development of d_{12} , we define the equivalent thermodynamic force and the maximal value of this force during the history of the loading

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

where α_1 and α_2 are the tension/shear coupling coefficients. It should be noted that this equivalent force, which governs the development of the progressive damage variable d_{12} , does not depend on the compression stresses in the warp and fill directions.

2.2. Behaviour under static loads

As for the unidirectional plies [10], a linear law with respect to the square root of \underline{Y} is chosen to describe the damage variable development

$$d_{12} = \left\langle \frac{\sqrt{\underline{Y}} - \sqrt{Y_o}}{\sqrt{Y_c} - \sqrt{Y_o}} \right\rangle_+, d_1 = d_2 = 0$$

$$\text{if } (d_{12} < 1 \text{ and } Y_{d1} < Y_{1f} \text{ and } Y_{d2} < Y_{2f})$$

$$\text{else } d_{12} = d_1 = d_2 = 1 \quad (4)$$

where the constant parameters Y_o 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.

2.3. Inelastic strain

After loading on a laminate [45]₈ (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 describe these strains by a plastic hardening model [4]. The loading-unloading hysteresis is not described.

The coupling between the damage and plasticity is taken into account by using the effective stress and the effective strain [10], which are defined as

$$\tilde{\sigma}_{12} \dot{\tilde{\epsilon}}_{12}^p = \sigma_{12} \dot{\epsilon}_{12}^p \text{ where } \tilde{\sigma}_{12} = \frac{\sigma_{12}}{(1-d_{12})} \text{ and } \dot{\tilde{\epsilon}}_{12}^p = \dot{\epsilon}_{12}^p (1-d_{12}) \quad (5)$$

It is assumed that the stresses σ_1 and σ_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 γ is the power law exponent. Then, by requiring the inelastic strain rates to be normal to the elastic domain function, we obtain

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

The yield conditions are then written as

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

2.4. Behaviour under fatigue loads

The model previously presented in Ref. [5] for unidirectional plies is a non-linear cumulative damage model, enables to describe the development of damage under both static and fatigue loading conditions. For this law, the evolution of the damage depends only on the maximal load over the cycle. This model was extended to woven plies taking into account the amplitude of the cycle load in the evolution of the damage. As for static cases, the validity scope of the model described here depends on the 'diffuse damage' phase (which is associated with small cracks) up to the first intralaminar macro-crack only (first ply failure model).

The material is assumed to be brittle and non-sensitive to the cyclic loading in the direction of the fibres. The in-plane

shear moduli is modified under the assumption that a gradual damage process is involved. The development of the damage depends on the maximal static and cyclic loads and their amplitude as well as on the level of damage involved. Furthermore, we define the cumulative damage where the shear damage variable is obtained by addition of two terms: one part is due to static loading and the other one is governed by fatigue loading

$$d_{12} = d_s + d_f \quad (10)$$

The static damage d_s evolution defined previously (relation (4)) is linear versus the square root of the associated equivalent force. For fatigue damage d_f evolution, experiments have shown its double dependency on maximal load and amplitude load (Fig. 4, $\sigma_{\max} = 150$ MPa, ratio of the minimal and maximal stresses: $R = 0.1$ and $R = 0.5$); so a law which respects this observation has been built

$$\frac{\partial d_f}{\partial N} = c * \left\langle \left(\sqrt{Y_{\max}} - \sqrt{Y_{\min}} \right)^\alpha * \left(\sqrt{Y_{\max}} \right)^\beta - Y_{of} \right\rangle_+,$$

$$Y_{\max}(t) = \sup_{\tau \in \text{cycle}(t)} (Y) \text{ and } Y_{\min}(t) = \min_{\tau \in \text{cycle}(t)} (Y) \quad (11)$$

where the constant parameter Y_{of} corresponds to the threshold in fatigue.

Examples of the evolution of the damage process in the case of a tension/tension fatigue test on a $[\pm 45^\circ]_{ns}$ laminate are shown in Fig. 5. The first level of damage ($d = 0.3$) was found to occur during the first cycle. The damage then increases slowly at each cycle, and the speed of evolution gradually increases until rupture occurs. In the simulation, the rupture of a $[\pm 45^\circ]_{ns}$ laminate was obtained by introducing a structural instability condition. Under static loading, this condition corresponds to a damage value $d = 0.5$, although this value can be greater under fatigue loading. This result is in line with what was observed experimentally.

During the fatigue loading process, residual strains can be observed. The cumulated plasticity evolution law, defined previously for a static load (Eqs. (5)–(9)), depends on the effective stresses. Because the fatigue damage increase during the cycles, the total damage increase and the effective stresses too. Using the same law (Eqs. (5)–(9)) in fatigue, the simulated inelastic strain evolution is in good agreement with the experiment evolution (Fig. 6).

3. Comparison with experimental tests in the case of structures

The high resistance of woven ply laminates to delamination [4], in addition to the fact that they are not subject to

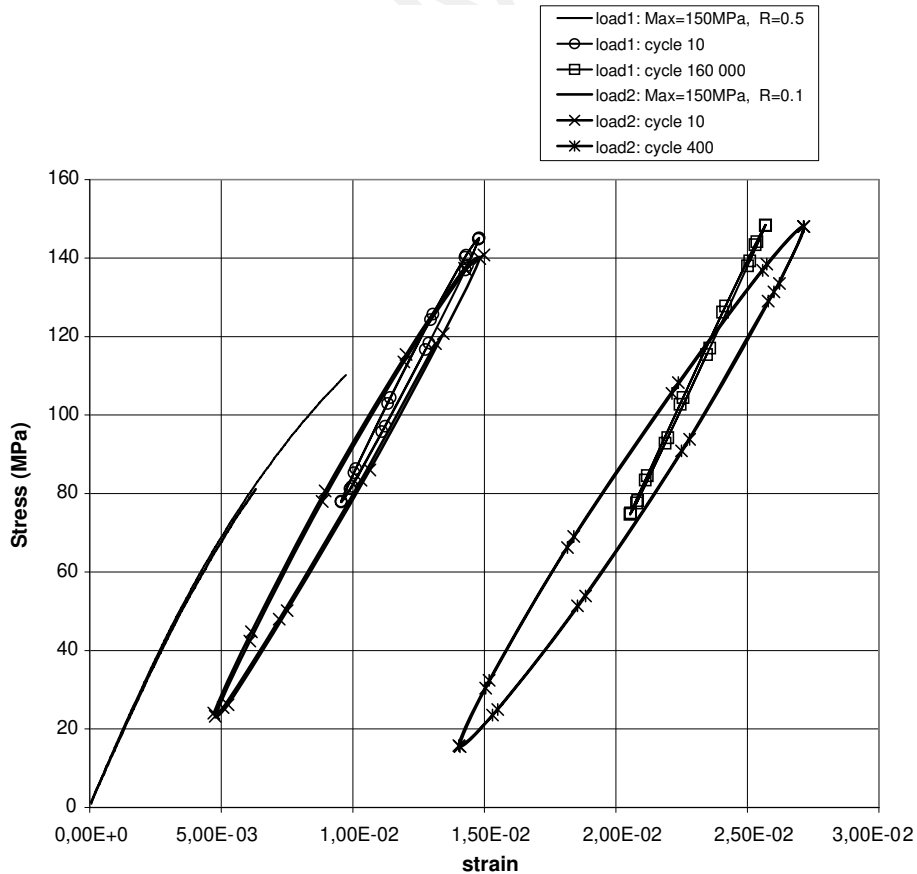


Fig. 4. Shear fatigue tests. Evolution of the stresses and the strains in fatigue for the same maximal load, $\sigma_{\max} = 150$ MPa, and two amplitudes (ratio of the minimal and maximal stresses: $R = 0.1$ and $R = 0.5$).

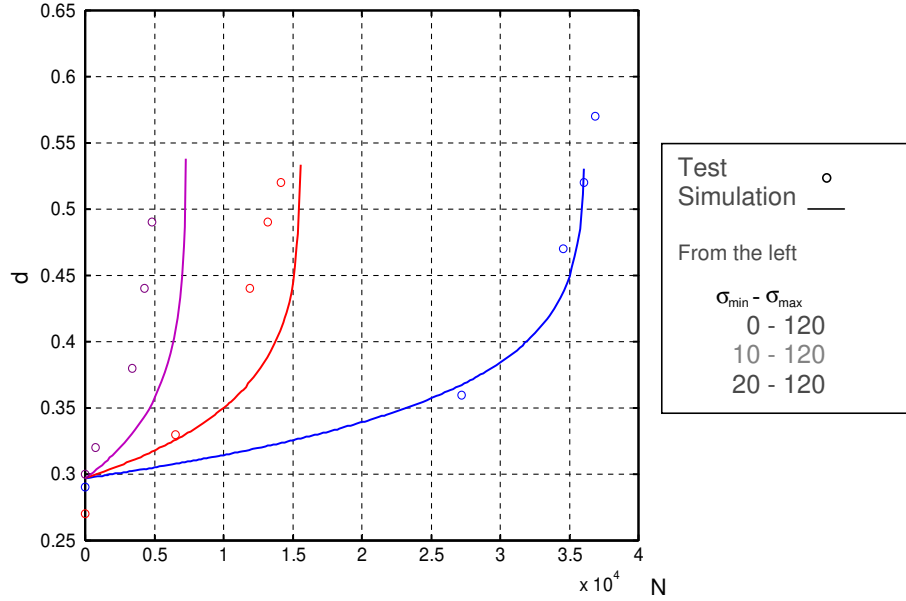


Fig. 5. Shear fatigue test. Evolution of the damage for the same maximal load over the cycle and three different amplitudes.

transverse rupture, allows to simulate the behaviour up to rupture of complex structures made of these materials. For this purpose, a simple finite element model of the shell type, based on plane stresses and accounting for the inelastic damage behaviour of the woven ply, can be used. The damage and inelastic strain evolution law under static load was implemented in Abaqus Standard via a user subroutine umat. It should be noted that this relatively simple modelling procedure is not suitable in the case of UD plies, in which transverse rupture and delamination processes resulting from the 3D effects mentioned above are responsible for the rupture of the laminate.

3.1. Behaviour of a perforated plate subjected to tension for a static load

In order to test the model, comparisons were made between the results of experimental tests and those of sim-

ulations involving a perforated plate under traction loading. The perforated plate was a 1.4 mm thick plate (160 × 50 mm) of woven ply G963/939 with a hole of 6.5 mm radius. Several orientations were tested: $[\pm 45]_s$, $[\pm 40]_s$, $[\pm 30]_s$, $[\pm 20]_s$ and $[0]_s$. For laminates showing a high level of damage ($[45^\circ]$ for example) the comparison was good but in the case of sequences showing brittle behaviour ($[0^\circ]$), the simulations underestimated the rupture. The local criteria generally used to describe the rupture in the fiber direction do not work in the case of a non-uniform stress field. This fact was pointed out by Withney and Nuismer [8] who proposed non-local criteria for a quasi isotropic UD laminate. Following this idea, we identify a first non-local criterion based on an average stress over

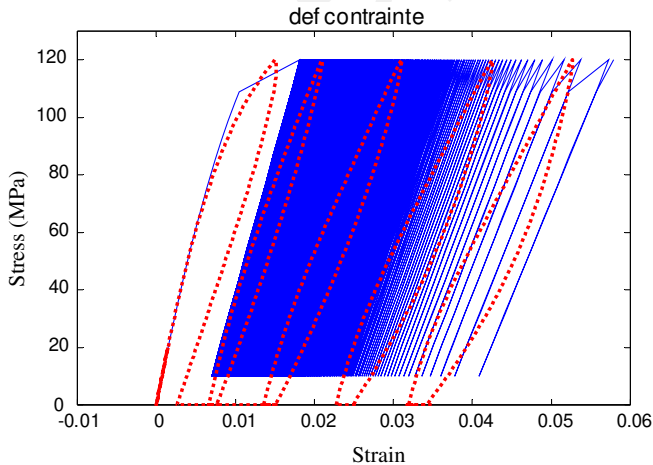


Fig. 6. Comparison of the experimental (...) and simulated (—) stress/strain evolutions in fatigue (same number of cycles at the end).

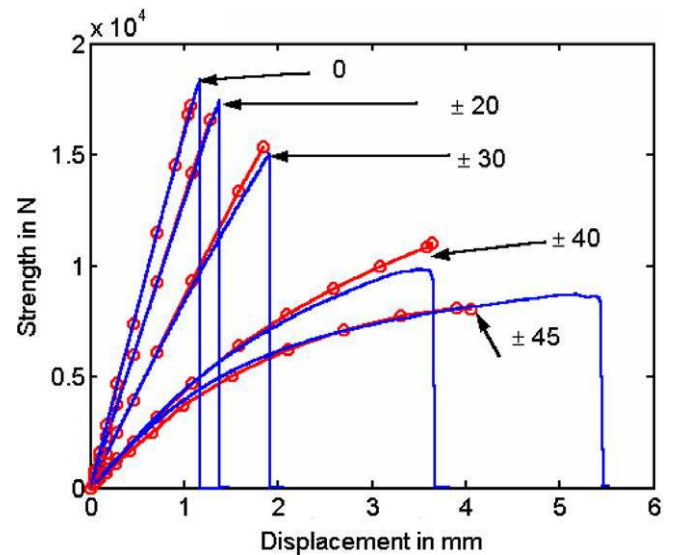


Fig. 7. Comparison of experiments (—) and simulations (o-o-o) for a plate with a hole. Evolution of the force with respect to the displacement.

an internal length for quasi isotropic woven ply laminates [9]. In order to study different laminates, we define a non-local criterion based on the average of the associated force (Y_{lf}) at the level of the ply by introducing a characteristic volume. This volume is a cylinder with the thickness of the ply and the radius depending on the material.

From the FE simulation point of view, the implementation of the non local criterion cannot be performed in a material routine at every gauss point. The criterion is evaluated in a post computation relative to the incremental calculation. The size of the mesh has to be smaller than the characteristic volume (for more than ten gauss points in the volume, the average is the same). Comparisons with the different stacking sequences are shown in Fig. 7.

3.2. Behaviour of a perforated plate subjected to tension for a fatigue load

To analyse the different mechanisms that appear in fatigue (evolution of the strain level with respect to the number of cycle, appearance of large cracks,...), a test on a plate [45°] with an open hole was performed using full field measurement [7]. For this structure, as in the case of static loadings, the apparition of the first macro-crack is very close to the complete rupture of the plate (less than 1% of total number of cycles). This result is probably not applicable in the case of structures showing very high stress gradients (an existent crack in the structure for example).

Again, the damage evolution law under fatigue load was implemented in Abaqus Standard via the user subroutine

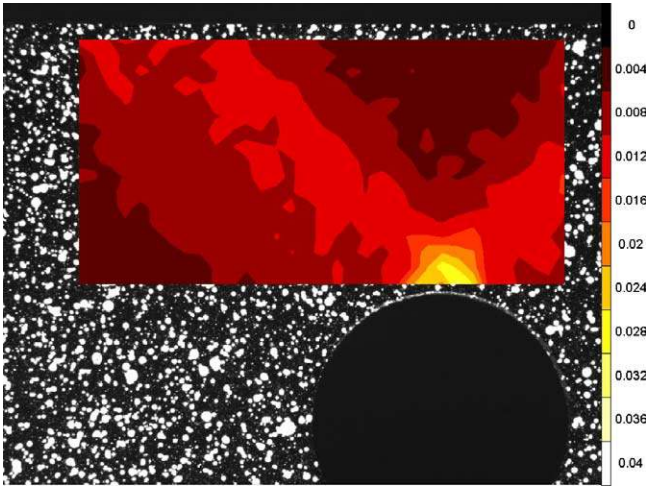


Fig. 8. Experiment strain level for the first cycle (maximal load).

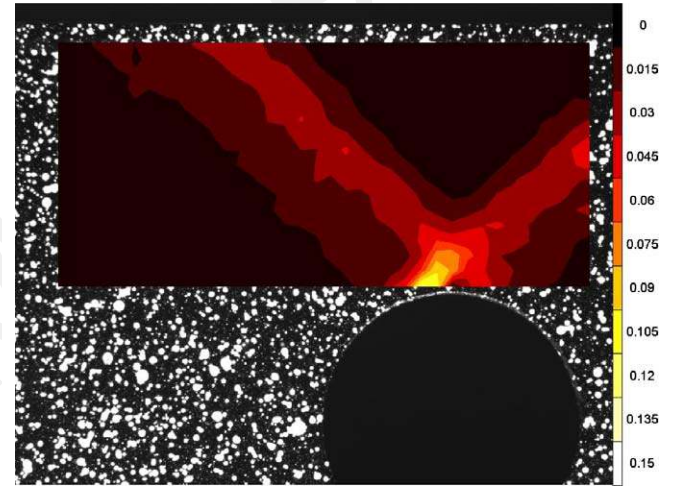


Fig. 10. Experiment strain level for the 45,000 cycle (maximal load).

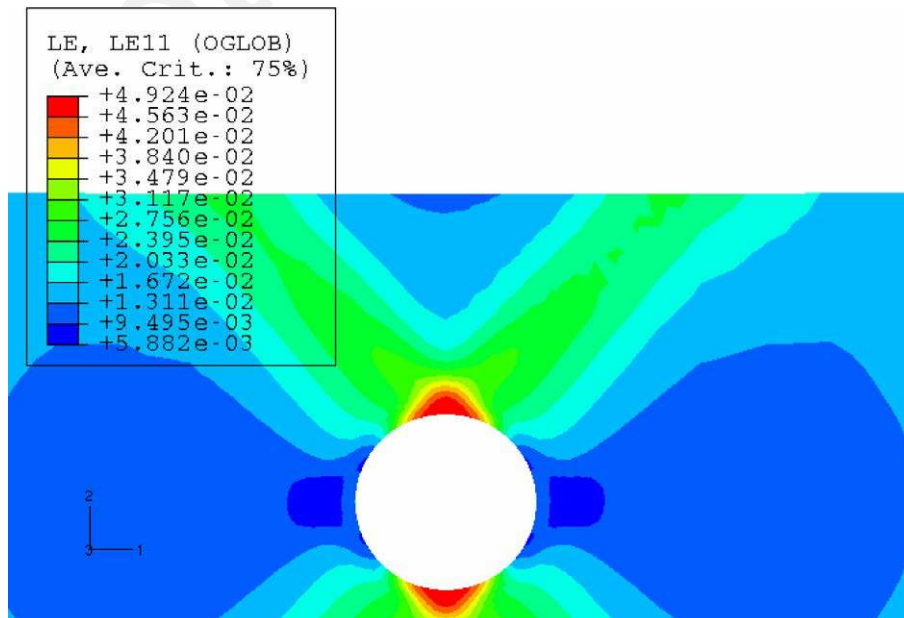


Fig. 9. Simulated strain level for the first cycle (maximal load).

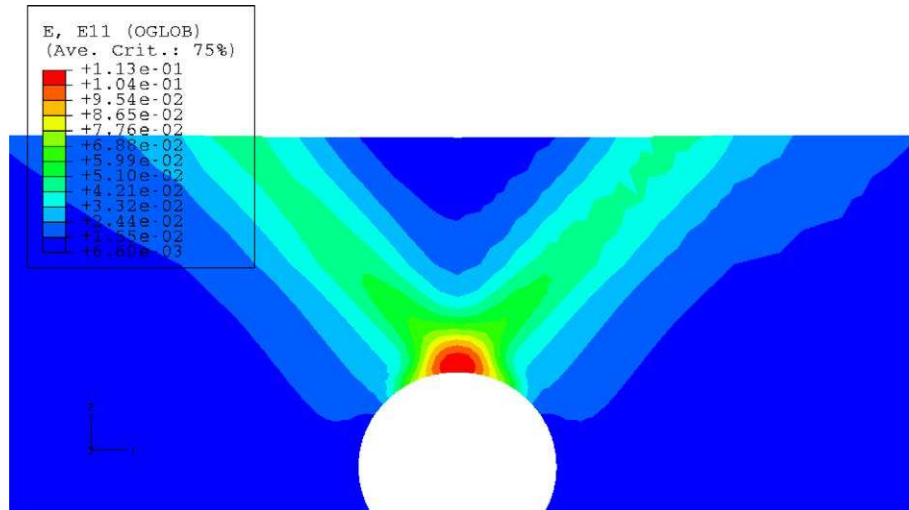


Fig. 11. Simulated strain level for the 30,000 cycle (maximal load).

umat. Figs. 8–11 show comparisons between the simulated and measured strain levels for the first cycle (Figs. 8 and 9) and before the rupture (Figs. 10 and 11). The simulated number of cycles up to rupture (30,000) is not too far of the experiment one (45,000). The comparisons of the evolution of the strains are good and it should be noted that the level of strain for the last cycle is three times the level of the first cycle. So, the strain and the stress distributions are different in space and in time between the first and the last cycles, with a non linear evolution in the structure. A classical approach using a finite element simulation with an elastic behaviour and a local (or non-local) criterion in fatigue is not able to describe the evolution of the stress distributions in the structure and the fatigue limit.

4. Conclusion

The rupture of woven ply laminates is less complex to model than UD ply laminates. Shear damage and inelastic strain evolution laws have been associated to a non-local criterion defined at the level of the ply, then implemented in a FEM code. This approach gives good correlations with experiments on laminated structures. In the case of static loadings, this first ply failure model is sufficient to describe the rupture of structures.

A non-linear cumulative damage model which takes into account the maximum and the amplitude of the cyclic loading has been proposed and implemented in the FEM code. A first experiment in fatigue with a perforated plate

(45° laminate) shows that this first ply failure model seems also to be sufficient to describe the rupture in the case of a structure with smooth stress gradients.

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