DAMAGE AND FAILURE OF LAMINATED COMPOSITE STRUCTURES UNDER VARIOUS MECHANICAL LOADS

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Keywords: Matrix damage, Fibre rupture, Composite structure, Stress concentration

Abstract

A non-linear cumulative *Continuum Damage Mechanics* (*CDM*) model for unidirectional and woven plies laminates undergoing static and fatigue loads has been developed. The *CDM* model describes the evolution of the matrix damage, consisting of small cracks running parallel to the fibers, which leads to a loss of stiffness in the transverse and shear directions. Even if the sizes of these cracks correspond to the thickness of the ply, they do not lead in general to the fracture of the laminate. On the other hand, the failure of one ply in the fibre direction is in general catastrophic for the laminate and the structure. A model defined at the ply scale to describe the fracture in the fibre direction for statics and fatigue loadings was proposed. This model is based on a reduction of strength in the fibre direction depending on the matrix damage. This phenomenon of reduction of strength in the fibre direction was observed on tubular specimens solicited in fatigue in torsion followed by a tensile or compressive test in the fibre direction.

In addition, an original approach based on a *Fracture Characteristic Volume* (*FCV*) has been developed to predict the fibre failure of laminated structures with stress concentrations. The *FCV* is a cylinder defined at the ply scale on which an average stress is calculated.

1. Introduction

The failure of laminated composite structures involves many mechanisms acting at various scales. The models based on *Continuum Damage Mechanics* (*CDM*) can described the progressive damage of the material which consists of the propagation of small matrix cracks parallel to the fibre direction [1,2]. Even if the size of these cracks corresponds to the thickness of the ply, they usually do not lead to the final failure of the laminate. On the other hand, the the failure of one ply in the fibre direction is in general catastrophic for the laminate and the structure.

A model defined at the ply scale to describe the fibre failure for static and fatigue loadings has been proposed [3]. The model describes a loss of strength in the fibre direction depending on the level of matrix damage. This phenomenon can be observed in a 0° (unidirectional or woven plies) tube by applying a cyclic torsion loading (shear in the ply) up to a high level of damage followed by a tensile or compression test in the fiber direction. The fatigue loading in shear leads to an important material degradation. In tension, the residual strength in the fibre direction observed is closed to the strength of the material when performing tensile test on dry fibre. The simple model presented here describes the progressive evolution of the transverse damage, for different kind of mechanical loadings, and the sudden drop in strength in tension for very high levels of transverse damage [3-4]. The different mechanical loadings can correspond to increasing monotonous loadings and cyclic loadings but also constant loadings. The last case of loading corresponds to pressurized tanks for example. Other tests on tubular specimen damaged after a torsion load and then loaded in compression show that the reduction of strength appears earlier for compression load in the fibre direction [5].

In addition, an original approach based on a *Fracture Characteristic Volume* (*FCV*) has been developed to predict the fibre failure of laminated structures with stress concentrations [4,6,7]. The *FCV* is a cylinder defined at the ply scale. Mean quantities (stress, energy,é) are calculated over the volume and compared to a maximum value obtained on an homogenous test. The geometrical parameters of the *FCV* are identified from a tensile test on a specimen with a stress concentration, such as a notched plate. The model and the nonlocal failure criterion were implemented in Abaqus. Some experiment/simulation comparisons on structures with stress concentration under various loads are presented here.

2. Matrix damage model ay the Unidirectional ply scale

2.1 Assumptions

A model based on the *Continuum Damage Mechanics* (*CDM*) has been developed to describe the damage evolution in composite material at the ply scale [1-3]. The damage is assumed to be uniform in the thickness of the ply. Modelling both static and fatigue loadings with the same model is allowed by the use of a non-linear cumulative law which describes the damage evolution according to the maximal load and the amplitude of the cyclic loading.
In the fibre direction, the *Unidirectional* (*UD*) ply shows a linear elastic behaviour when applying a tensile loading until the final brittle failure. In the transverse and shear directions, the response is non linear because of the damage which leads to a loss of stiffness. The damage kinematics was described by three internal damage variables:

- d_1, whose evolution represents the linear elastic behaviour and the brittle failure of the fibres observed when applying a tensile load in the longitudinal direction
- d_2, which models the loss of transverse stiffness observed when applying transverse and shear loadings
- d_{12}, which describes the loss of shear stiffness due to transverse and shear loadings.

The progressive development of damage d_2 and d_{12} depends on the tensile load as well as on the shear load, which generates the matrix cracks. In the assumption of plane stress and small perturbation, the strain energy in the ply can be written as follow [1]:

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

where $<.>_+$ is the positive part and $<.>_-$ is the negative part. The tensile energy and the compressive energy are separated in order to describe the unilateral nature of the damage process due to the opening and closing of the cracks. The thermodynamic forces associated with the internal tensile and shear variables d_1 , d_2 and d_{12} are defined as follow:

$$\begin{cases} Y_{d_i} = \dfrac{\partial E_D^{ps}}{\partial d_i} = \dfrac{\langle\sigma_i\rangle_+^2}{2E_i^0(1-d_i)^2} & \text{with } i = 1, 2 \\ Y_{d_{12}} = \dfrac{\partial E_D^{ps}}{\partial d_{12}} = \dfrac{(\sigma_{12})^2}{2G_{12}^0(1-d_{12})^2} & \end{cases} \quad (2)$$

The development of internal variables depends on these thermodynamic forces. Under tensile loading conditions, d_1 suddenly develops to model the brittle behaviour in the fibre direction. So, d_1 is defined as:

$$\begin{cases} d_1 = 0 & if\ Y_{d_1} < Y_1^{\max} \\ d_1 = 1 & if\ Y_{d_1} \geq Y_1^{\max} \end{cases} \quad (3)$$

where $Y_1^{\max}$ is the parameter defining the ultimate force in the fibre direction

2.2 Damage evolution laws

The cumulative damage evolution law is defined as follow. The damage variables in the transverse and the shear directions, denoted respectively d_2 and d_{12}, are calculated as the sum of the terms due to static and fatigue loadings [2-4].

$$d_2 = d_2^{(s)} + d_2^{(f)} \tag{4}$$

As proposed in [1], the shear damage d_{12} is taken proportional to the transverse damage d_2. This choice is based on the fact that the cracks are parallel to the fibers and their effect on the transverse and shear modulus is the same.

$$d_{12} = c\, d_2 \tag{5}$$

In the case of static loading, the tension/shear coupling during the development of d_2 is accounted for by the following equivalent thermodynamic force:

$$Y_{eq} = a\left(Y_{d_2}\right)^n + b\left(Y_{d_{12}}\right)^m \tag{6}$$

where a, b, m and n are material parameters specifying the tension/shear coupling. The evolution law for the damage is written as:

$$d_2^{(s)} = \left\langle 1 - e^{-\left(Y_{eq} - Y_0^s\right)} \right\rangle_+ \tag{7}$$

where the constant parameter Y_0^s corresponds to the threshold value of the development of d_2 (which ranges from 0 to 1).
In the case of fatigue loading, the damage evolution depends on the maximal load $Y_{d_i^{(f)}}$ and the amplitude of the loading $\Delta Y_{d_i^{(f)}}$ during a cycle. The damage evolution law is then written as:

$$\frac{\partial d_2^{(f)}}{\partial N} = \left(1 - d_2\right)^{\gamma} \left\langle a_f \left(Y_{d_2^{(f)}}\right)^{\beta_1} \left(\Delta Y_{d_2^{(f)}}\right)^{\beta_2} + b_f \left(Y_{d_{12}^{(f)}}\right)^{\beta_3} \left(\Delta Y_{d_{12}^{(f)}}\right)^{\beta_4} - Y_0^f \right\rangle_+ \tag{8}$$

Where Y_0^f is the threshold value of the development of $d_2^{(f)}$

$$\Delta Y_{d_2^{(f)}} = \frac{\left(\left\langle \sigma_2^{\max} \right\rangle_+ - \left\langle \sigma_2^{\min} \right\rangle_+\right)^2}{2\, E_2^0 \left(1 - d_2\right)^2} \quad and \quad \Delta Y_{d_{12}^{(f)}} = \frac{\left(\sigma_{12}^{\max} - \sigma_{12}^{\min}\right)^2}{2\, G_{12}^0 \left(1 - d_{12}\right)^2} \tag{9}$$

2.3. Inelastic strain in the shear direction

After loading has been applied to a $(+45,-45)_{ns}$ laminate, inelastic strains are observed. These strains may result from the slipping/friction process occurring between fibre and matrix as the result of the damage. Although inelastic strain can also be observed during tensile test on 0° and 90° laminates, only the inelastic strain in the shear direction is relevant. A kinematic hardening model was used to describe the inelastic shear strain evolution.
The coupling between the damage and the plasticity is accounted for by the effective stress and the effective strain [1], which are written as:

$$\tilde{\sigma}_{12} = \frac{\sigma_{12}}{(1 - d_{12})} \quad and \quad \tilde{\varepsilon}_{12}^p = \varepsilon_{12}^p (1 - d_{12}) \tag{10}$$

It is assumed that stresses σ_1 and σ_2 do not influence the elastic field domain defined by:

$$f = \left| \tilde{\sigma}_{12} - X(\tilde{\varepsilon}_{12}^p) \right| - R_0 \tag{11}$$

where R_0 is the initial inelastic strain threshold and X is the hardening parameter.

3 Fibre tensile failure criterion

3.1 Damage influence on the fibre failure

During the fatigue loading, crack density increases in the transverse direction and this damage leads to a decrease of the stiffness. In the longitudinal direction, the damage prevents the load transfer between fibres. Fibre failure can then occur even if the maximal stress usually measured in the case of homogeneous tension test is not reached. This phenomenon was not observed in the case of static loading due to the low crack density compared to the case of fatigue loading where the damage can reach a very high level.
Experimental tests were performed to study this phenomenon which can lead to premature failure of laminate. Specifics tubes were manufactured with Glass/Epoxy unbalanced woven ply. The tube shape was studied so that the strain field was quasi-homogeneous in the central area (Fig. 1). The lay-up in the central area was $(0)_3$. A torsion cyclic loading was applied to the tubes and generates matrix damage. The shear stress/shear strain curve for the torsion fatigue is plotted in Fig. 2 (left). The shear strain is measured with a torsional extensometer. The loss of stiffness, which characterizes the evolution of the damage, can be observed on Fig. 2 (left).

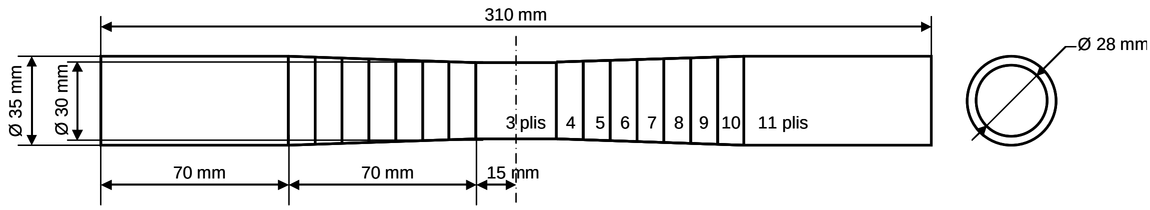

Figure 1. Geometry of the tube

The damage is calculated from the variation of the shear modulus ($d_{12} = 1 - G_{12}/G_{12}^0$). Various levels of damage were obtained according to the number of cycles applied. Then, the tubes were loaded in static tension until the final failure to estimate the residual strength of the fibres. The influence of the damage on the failure strength in the fibre direction under traction has been published in [5]. The matrix damage influence on the fibre strength can be taken into account with the simple criterion:

$$Y_{d_1} \leq Y_{d_1}^{\max}(d_2) \tag{12}$$

where the thermodynamic force Y_{d_1} is proportional to the longitudinal stress (eq.(3)). In the case of traction, $Y_{d_1}^{\max}$ evolves sharply between two values according to a threshold value of d_2. In the case of static loading, the level of damage does not usually reach the threshold and the criterion (12) is equivalent to a maximum stress criterion. But in the case of fatigue loading with a high number of cycles, the level of the damage cannot be neglected. The reduction of strength appears earlier for compression load in the fibre direction [5].

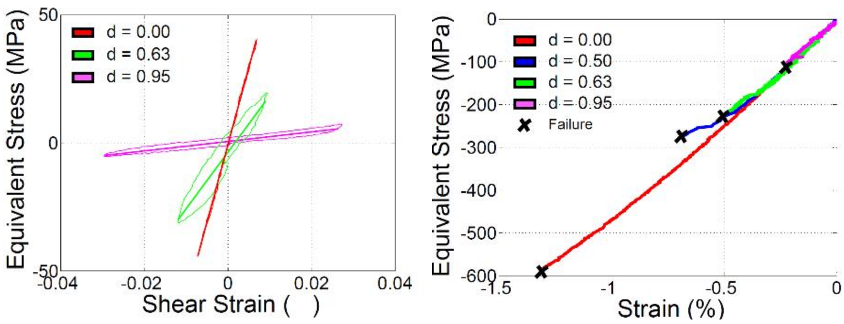

Figure 2. Compression after torsion on tubes: Fiber strength in compression (rigth) after matrix damage in shear (left).

3.2 Application of the model on unbalanced woven plies laminates

The model was applied to Glass/Epoxy unbalanced woven ply. The woven ply was modelled by two *UD* plies with different thicknesses to take into account the different proportions of fibres in the warp and the weft directions (Fig. 3). The parameters of the elastic and damage laws of both UD plies were evaluated from the mechanical response of unbalanced woven ply laminates. In the case of fatigue loading especially, the influence of the ply thickness on the damage evolution cannot be neglected. So, the damage properties for the thin and the thick ply need to be defined separately. The identification of the material properties required by the model is detailed in [5].

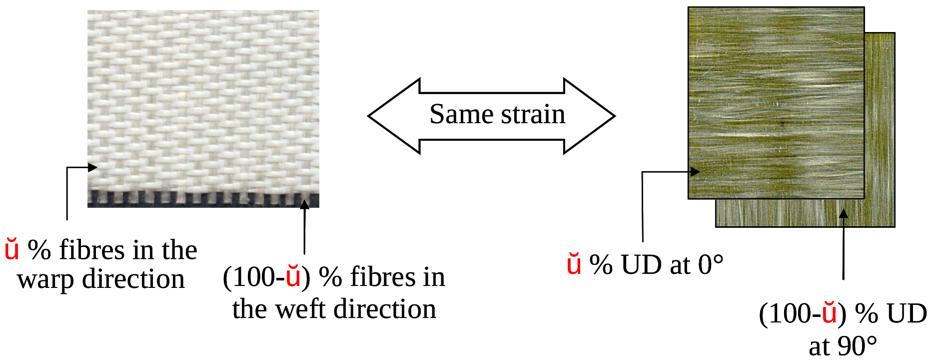

Figure 3. Assumption for woven plies

Dumbbell shaped specimens [6] were used for the fatigue tests in order to avoid premature failure in the tabs. The experimental fatigue loading tests on 90° laminates are shown in Fig. 4 (left). Tthe influence of the amplitude of the load and the *R* ratio ($R = \sigma_{\min} / \sigma_{\max}$) is small. The experimental and simulated results were compared after identifying the coefficients of the law (8) in the case of the 0° and 90° laminates. These results showed relatively good agreement regarding the current state of development of the parameters identification process (the $\boldsymbol{b}_2$ coefficient (eq. 8) is taken to be equal to 0, which leads to cancelling the influence of the load amplitude in the transverse direction of the UD plies).

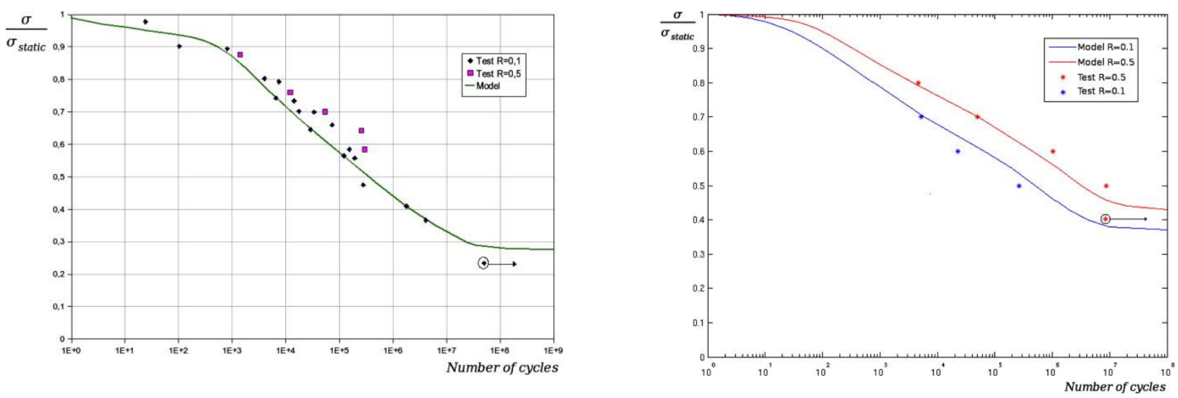

Figure 4. S-N curves for 90° (left) and (+45°,-45°)s (right) unbalanced woven ply in tension

The results of the experimental fatigue tests on (+45°,-45°) are shown in Fig. 4 (rigth). The influence of the *R* ratio is more important with this laminate, where the level of shear stress is a significant factor. As previously observed in the case of balanced carbon/epoxy woven plies [4], the influence of the *R* ratio is the predominant factor in shear loading case. The experimental and simulated data were compared after identifying the coefficients of the law (8) in the case of the (+45°,-45°) laminates (Figure 8). A good agreement between the test and the simulation can be observed. The influence of the *R* ratio was correctly taken into account.

4. Structures with stress concentration

4.1 Fracture Characteristic Volume

The previous studies led to observe a strong underestimation of the failure strength when a local criterion was used to predict the failure of laminated structure [7] with stress concentration. An original approach based on a *Fracture Characteristic Volume* (*FCV*) has been developed to account for the influence of stress concentrations [7-4]. The *FCV* is a cylinder defined at the ply scale as the volume $V = hS$, where h is equal to the thickness of the ply and S is the in-plane area (Fig. 5).
The non local fracture criterion was defined in the case of static loading as:

$$\overline{Y_{d_1}} = \frac{\left(\frac{1}{V}\int_V \langle \sigma_1 \rangle_+ \, dV\right)^2}{2\,E_1^0} \qquad and \qquad \overline{Y_{d_1}} < Y_{d_1}^{\max} \tag{13}$$

where $\overline{Y_{d1}}$ is the mean thermodynamic force associated to the damage variable in the longitudinal direction d_1 and $Y_{d_1}^{\max}$ is a material property which needs to be identified.

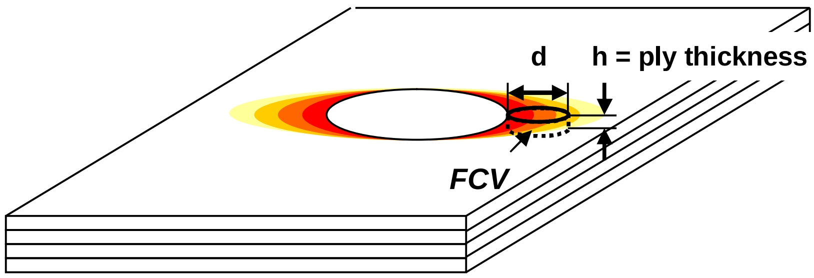

Figure 5. Non local failure criterion based on a *Fracture Characteristic Volume* (*FCV*) . Assumption for woven plies

The extension to fatigue loading led to modify the criterion and take into account the influence of matrix damage on the tensile fibre failure [6]. The criteria (13) can now be written as:

$$\begin{cases} \overline{Y_{d_1}} = \dfrac{\left(\dfrac{1}{V_f}\displaystyle\int_{V_f} \langle \sigma_1 \rangle_+ \, dV\right)^2}{2\,E_1^0} \qquad and \qquad \overline{Y_{d_1}} < Y_{d_1}^{\max}(\overline{d_2}) \\ \overline{d_2} = \dfrac{1}{V_f}\displaystyle\int_{V_f} d_2 \, dV \end{cases} \tag{14}$$

In the case of fatigue, if the level of damage is high, the degraded material can be seen as a different material compared to the healthy material and can require a new identification of the *FCV* (V_f).

4.2. Plates with stress concentrations in static

The use of the non local criterion was applied to structures with high stress gradients, such as plates with holes, circular notches and saw cut. The ultimate strength was measured experimentally for several laminates: $(0)_8$, (90)8, (QI), $(\pm 18)_{4S}$ and $(15)_8$.

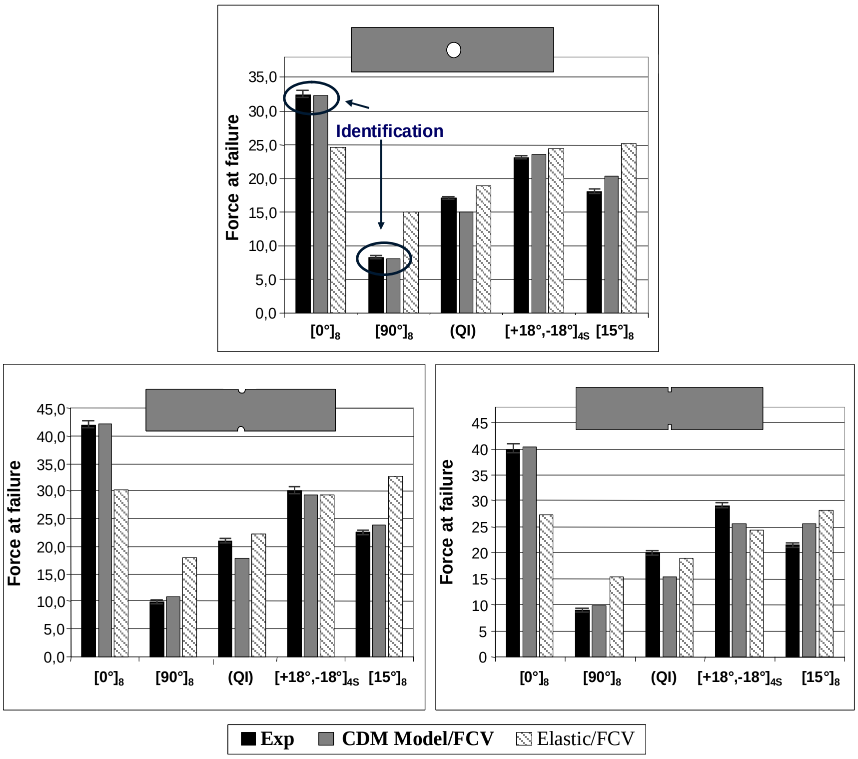

Figure 6. Comparison of experimental and numerical predictions for different laminates and plates with holes, notches and saw cut (failure load in kN).

The results of the approach presented here (Fig. 6), in which non linear behaviour is associated to the non local failure criterion (*CDM* model/*FCV*), matched the experimental data (Exp) quite well. The failure occurs when the failure criterion is reached in an *FCV*.
The *FCV* can be used with an elastic linear model. With a linear behaviour, the computation time and the number of parameters to be identified are highly reduced. Figure 8 gives results obtained with this method (*Elastic*/*FCV*). In the case of (QI) and $(\pm 18)_{4s}$ laminates, this method gives good results. In the case of $(0)_8$ and $(90)_8$ laminates, the results are less accurate because the damage cannot be neglected. Around a geometrical singularity, the level of damage is very high, which influences the stress distribution. In the last case studied, the $(15)_8$ laminate showed a very non linear behaviour. So, the elastic law did not work.

4.3 Open hole plate in fatigue

Open hole $(+18,-18)_{2S}$ plates were manufactured with Glass/Epoxy unbalanced woven ply. The dimensions of the plates were 300mm long and 45mm width and a diameter of 13mm for the hole. A cyclic loading was applied on the plates. The ratio between the minimal stress and the maximal stress was equal to 0.1. Different values of the maximal stress were studied.
The model was applied to the open hole plates. The failure of the laminated structures was defined by the criterion (14) with the same *FCV* as for static load ($V_f = V$). A first ply failure approach was applied. The experimental data and the numerical simulations are compared in Fig. 7. The size of the damage zone increases with the number of cycles. The model matches quite well the experimental tests, which means that both damage and stress concentration have to be taken into account to predict the failure of laminated structures in the case of tensile fatigue loading.
Few fatigue tests were performed on specimens with stress concentrations. For this laminate and material, it was not necessary to change the size of *FCV* in fatigue but it is probably not the case for all materials (first results with carbon fibre).

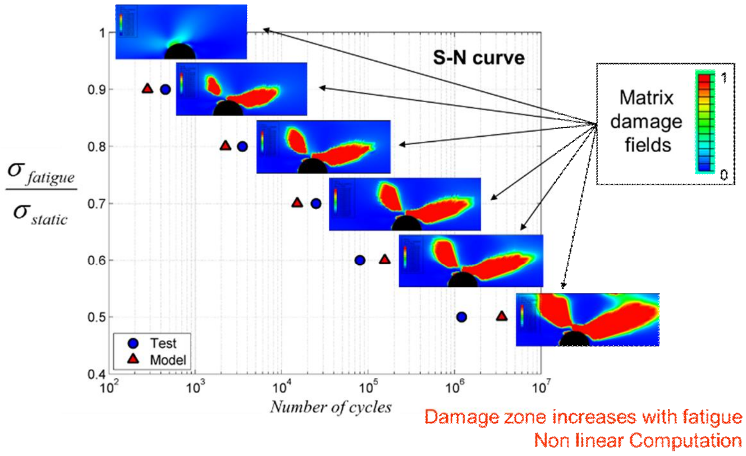

Figure 7. SN curve of a plate with a notch in traction/traction

5. Conclusion

A fibre failure model for static and fatigue loads, based on a description of the loss of strength in the fibre direction for high levels of transverse damage, was presented. The simple criterion based on a *Fracture Characteristic Volume* previously developed to predict the failure of laminated structure under static loading was extended to the case of fatigue loading. Experimental tests on open hole plate were performed. The results obtained with the model matched the first experimental data fairly well.
The relation between the damage, the stress concentration and the tensile fibre failure needs to be studied with more accuracy, in particular the influence of the damage on the size of the *FCV*.

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