A NEW THERMODYNAMICAL FATIGUE DAMAGE MODEL FOR SHORT GLASS FIBRE REINFORCED THERMOPLASTIC COMPOSITES

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Abstract

The present work is a contribution to the phenomenological modelling of fatigue damage in short glass fibre reinforced thermoplastic matrix composites. It is a first part of a continuing work which intends to develop a new damage model into the framework of continuum damage mechanics. The developed model is implemented into the finite element implicit code ABAQUS through user defined material subroutine UMAT. The latter is aimed at predicting the fatigue damage accumulation and the subsequent stiffness reduction in short fibre reinforced thermoplastic composites. The developed model is intended to improve the fatigue life predictions and hence the numerical simulations of structures durability. The developed damage modelling will be used to optimize composite parts in automotive industry. Several simulations have been conducted upon a glass (E) /thermoplastics matrix to emphasize and to understand the effect of material parameters on the damage kinetic and accumulation under cyclic loading.

1 Introduction

The current trend in the automotive industry is the use of fibre-glass-reinforced thermoplastics in various automotive applications. These composite materials are gradually replacing steels, light alloys, and in some cases expensive reinforced thermosets. They are used towards producing safe and lightweight vehicles.

For reinforced thermoplastics, safety against fatigue damage is considered as the decisive factor for an optimum part design. However, the optimal design must be assessed with a minimum of expensive prototype testing. To achieve this aim, material and structures computations must be carried out numerically in terms of strength and damage accumulation due to cyclic loading.

In case of composite materials, the damage is characterised by the material irreversible degradations. The basic modes of this degradation have been studied in case of static and cyclic loads [1]. This damage consists mainly in onset, coalescence and propagation of micro-cracks. For cyclic loading, composites materials exhibited a stiffness reduction from the first cycle and increases progressively leading hence to macroscopic failure. In glass fibre reinforced thermoplastic composites subjected to cyclic loading, the literature shows that the damage evolution occurs according to three stages:

Stage 1: corresponds to the onset of “damage zones”, which contain a multitude of microscopic cracks and other forms of damage, such as matrix voids. Hence damage starts very early, after only a few or a few hundred loading cycles. It gives rise to a sharp initial decrease of the composite’s stiffness.

Stage 2: This stage corresponds to the coalescence and the propagation of the micro-discontinuities created during the first stage. This propagation concerns notably the fibre-matrix interface zones. A very gradual deterioration of the material is then observed. This stage is a behaviour accommodation and is characterised by a relatively stable reduction of the composite stiffness.

Stage 3: the last stage is charachterised by a dramatic and instable damage accumulation due to the appearing of fibre fracture and macroscopic cracks propogation. The third damage stage may bring about a rapid stiffness reduction leading to the total material failure.

For fatigue life prediction, it is critical to model the damage evolution accurately since fatigue analysis puts great demand on model accuracy. Nevertheless, the fatigue damage model cannot be too complex since the analysis is time-consuming. Simplifications and idealizations have to be made without too much expense on solution accuracy. The finite element method (FEM) yields an approximate solution. As opposed to static yield criteria, there is no universal fatigue assessment method, but rather a multitude of methods that must be considered.

This paper intends to develop a phenomenological modelling of fatigue damage in short glass fibre reinforced thermoplastic matrix composites. The damage, conceded as an internal state variable, is coupled with a constitutive modelling. The damage evolution, corresponding to the material degradation under cyclic mechanical loading, is quantified in thermodynamic framework. A new dissipation potential function is proposed and introduced into the framework of continuum damage mechanics to capture the damage kinetic specific to short glass fibre reinforced thermoplastic. The proposed damage accumulation model appears to accomplish this with a good accuracy for the studied materials. Numerical examples are given to demonstrate the application of proposed damage model for composite materials subjected to cyclic loading and to show that the versatility of the proposed model and to conduct parametric and sensitivity studies.

2 Problem description

Ladevèze [3] has developed a fatigue damage law for composite materials. The above is mainly used for unidirectional or laminated thermoset composites [4]. The damage law was developed within the framework of thermodynamics irreversible processes. Primarily, the damage model initially proposed by Ladevèze has been numerically implemented into a FE code (ABAQUS). This has been performed to attempt a prediction of the fatigue damaged behaviour of a short glass fibre reinforced polyamide (PA 6-6) or polypropylene. It has been noticed that the damage predictions obtained by the Ladevèze model (figure 1) are different from those generally observed for short glass fibre reinforced thermoplastic composites [5]. Indeed, the damage kinetic predicted by Ladevèze model is mainly reduced during the first cycles whereas it has been observed that a high damage kinetic occurs at the first stage of damage. However, for thermoplastic reinforced composites, the damage evolution presents three stages. The first one is associated with the onset of micro-cracks giving rise to a fast damage increase and consequently a rapid stiffness reduction. In the second stage, the damage evolution is very slow; it corresponds to crack propagation and a behaviour accommodation appearing as a relatively stable stiffness reduction. The third stage describes dramatic damage propagation prior to the macroscopic failure of the material [6-10]. As mentioned in the introduction.

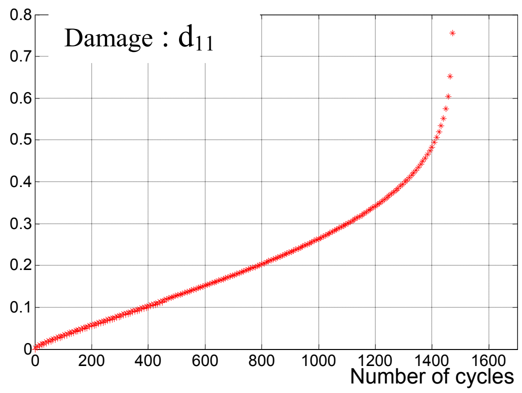

Fig. 1. Damage curve evolution predicted according to Ladevèze model [3].

In an attempt to predict the three damage stages observed for short glass fibre reinforced thermoplastics, the present paper deals with a new formulation of a damage model based on the Ladevèze model. To this end, the dissipation potential (φ) has been modified by adding an exponential function leading to five additional terms. It's worth noting that the number of model parameters becomes twice more than the initial number. In the following sections, the new formulated model is noted as MNL (Meraghni-Nouri-Lory) and has been also implemented into

ABAQUS FE code through a user subroutine UMAT.

3 Three dimensional damage modelling

To develop an accurate modelling taking into account the observed three damage stages, the Ladevèze model was reformulated and modified. A new expression of the potential dissipation (φ) was proposed by adding terms in exponential form. First, the theoretical background of the damage modeling is given.

3.1 Theoretical background

The model presented here is developed within the framework of the thermodynamics of the irreversible phenomena. The volumic energy of elastic strain, which is considered as a thermodynamic potential and is given by:

$$2W_e = C_{11}\varepsilon_{11}^2 + 2C_{22}\nu_{12}\varepsilon_{11}\varepsilon_{22} + C_{22}\varepsilon_{22}^2 + G_{12}\gamma_{12}^2 + G_{13}\gamma_{13}^2 + G_{23}\gamma_{23}^2 \quad (1)$$

C_{ij} represent the elastic behaviour constants, and G_{ij} are the shear modulus . These constants are given by :

$$C_{11} = \frac{E_1}{1-\upsilon_{12}\upsilon_{21}}; \quad C_{22} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}}; \quad (2)$$
$$\gamma_{12} = 2\varepsilon_{12}; \ \gamma_{13} = 2\varepsilon_{13}; \ \gamma_{23} = 2\varepsilon_{23}\gamma_{12}$$

The symmetry relations arising from the existence of a thermodynamic potential give:

$$\frac{C_{11}}{C_{22}} = \frac{E_{11}}{E_{22}} = \frac{\upsilon_{11}}{\upsilon_{22}}$$

It comes $\upsilon_{21}C_{11} = \upsilon_{12}C_{22}$ and according to the definition of C_{11} one notices that:

$$C_{11}(1-\upsilon_{12}\upsilon_{21}) = E_1 \Rightarrow C_{11} = E_1 + \upsilon_{12}\upsilon_{21}C_{11} = E_1 + \upsilon_{12}^2 C_{22} \quad (3)$$

In this form, the value of the stress $\sigma_{22} = C_{22}(\varepsilon_{22} + \upsilon_{12}\varepsilon_{11})$ appears clearly. The elastics deformation energy (1) can thus be written as follows:

$$\begin{aligned} 2W_e &= E_1\varepsilon_{11}^2 + C_{22}\upsilon_{12}^2\varepsilon_{11}^2 + 2\upsilon_{12}C_{22}\varepsilon_{11}\varepsilon_{22} + C_{22}\varepsilon_{22}^2 \\ &\quad + G_{12}\gamma_{12}^2 + G_{13}\gamma_{13}^2 + G_{23}\gamma_{23}^2 \\ &= E_1\varepsilon_{11}^2 + C_{22}(\varepsilon_{22} + \upsilon_{12}\varepsilon_{11}) + G_{12}\gamma_{12}^2 \\ &\quad + G_{13}\gamma_{13}^2 + G_{23}\gamma_{23}^2 \end{aligned} \quad (4)$$

3.2 Damage variables

According to the continuum damage mechanics, the damage is introduced as an internal state variable (d_{ij}). It is coupled to elastic behaviour. Elastic moduli of the damaged material are then given by:

$$\begin{aligned} E_1 &= E_1^0(1-d_{11}); \\ C_{22} &= C_{22}^0(1-d_{22}) \\ G_{12} &= G_{12}^0(1-d_{12}); \\ G_{13} &= G_{13}^0(1-d_{13}); \\ G_{23} &= G_{23}^0(1-d_{23}) \end{aligned} \quad (5)$$

Superscript 0 indicates the non damaged state of the material.

3.3 Evolutions law

The introduction of damage variables into expression (4) gives Eq. (6) which represents the damaged deformation energy. In what follows, this equation will be used throughout the study.

$$\begin{aligned} 2W_e &= E_{11}^0(1-d_{11})\varepsilon_{11}^2 + C_{22}^0\langle\varepsilon_{22} + \upsilon_{12}\varepsilon_{11}\rangle_-^2 \\ &+ C_{22}^0(1-d_{22})\langle\varepsilon_{22} + \upsilon_{12}\varepsilon_{11}\rangle_+^2 + G_{12}^0(1-d_{12})\gamma_{12}^2 \\ &+ G_{13}^0(1-d_{13})\gamma_{13}^2 + G_{23}^0(1-d_{23})\gamma_{23}^2 \end{aligned} \quad (6)$$

As proposed by Ladevèze the initial model assumes that the cracks behave distinctly under tensile and compression stress state. Consequently, two terms are introduced in the equation (4): (<X>+) and (<X>-). They represent respectively the positive and the negative part of the variable X.

In equation (6), it is worth noting that only the tensile stress will contribute to the damage accumulation.

The evolution laws of the damage variables are given by introducing the thermodynamics of generalised standard materials.

The thermodynamic variables associated to the damage variables (d_{ij}) are called dual variables and are thus defined by:

$$Y_{ij} = \frac{\partial W_e}{\partial d_{ij}} \tag{7}$$

As indicated in the introduction, the damage evolution in reinforced thermoplastic composites occurs according the well-known three stages. To approach this evolution numerically, several laws have been proposed [3-5]. These are of power type and generally use the thermodynamic dual variables associated to the internal variables to express damage evolution. These laws present a more or less significant number of parameters. The major difficulty lies in the experimental identification, and in the physical interpretation of these parameters.

In this work a new formulation is proposed to express the dissipation potential. As given by equation (8), a second term is added to the initial Norton's law introduced in the initial modelling. Added terms are exponential functions of the cycle number (N). The proposed formulation allows modelling the first stage of the damage evolution. It should be stressed that the new expression yields to the use of four material parameters to model the evolution of each damage variable. The overall parameters number of the model is hence 20 parameters instead of the Ladevèze model requiring only 10 parameters to describe the damage evolution.

$$\varphi = \frac{\alpha_{ij}}{1+\beta_{ij}} Y_{ij}^{\beta_{ij}} + \gamma_{ij} \frac{Y_{ij}^2}{2} e^{-\lambda_{ij} N} \tag{8}$$

$$\begin{aligned}\varphi = {} & \frac{\alpha_{11}}{1+\beta_{11}} Y_{11}^{\beta_{11}} + \gamma_{11} \frac{Y_{11}^2}{2} e^{-\lambda_{11} N} + \frac{\alpha_{11}}{1+\beta_{11}} Y_{11}^{\beta_{11}} \\ & + \gamma_{11} \frac{Y_{11}^2}{2} e^{-\lambda_{11} N} + \frac{\alpha_{11}}{1+\beta_{11}} Y_{11}^{\beta_{11}} + \gamma_{11} \frac{Y_{11}^2}{2} e^{-\lambda_{11} N} \\ & + \frac{\alpha_{11}}{1+\beta_{11}} Y_{11}^{\beta_{11}} + \gamma_{11} \frac{Y_{11}^2}{2} e^{-\lambda_{11} N} + \frac{\alpha_{11}}{1+\beta_{11}} Y_{11}^{\beta_{11}} \\ & + \gamma_{11} \frac{Y_{11}^2}{2} e^{-\lambda_{11} N}\end{aligned} \tag{8bis}$$

The Evolution laws are then written from the dissipation potential according to the second law of thermodynamics defined by the equation:

$$\dot{d}_{ij} = \frac{\partial \varphi}{\partial Y_{11}} = \frac{\partial d_{ij}}{\partial N} \tag{9}$$

Damage rates corresponds to the damage kinetics and are obtained from the dissipation potential as given by the following expressions

$$\begin{aligned}\frac{d(d_{11})}{d(N)} = \frac{d\varphi}{dY_{11}} = {} & \frac{\alpha_{11}\beta_{11}}{1+\beta_{11}} \left(\frac{1}{2} E_1^0 \varepsilon_{11}^2 \right)^{\beta_{11}-1} \\ & + \gamma_{11} \left(\frac{1}{2} E_1^0 \varepsilon_{11}^2 \right) \left(e^{-(\lambda_{11} N)} \right)\end{aligned} \tag{10}$$

$$\begin{aligned}\frac{d(d_{22})}{d(N)} = {} & \frac{d\varphi}{dY_{22}} \\ = {} & \frac{\alpha_{22}\beta_{22}}{1+\beta_{22}} \left(\frac{1}{2} C_{22}^0 \left(\upsilon_{12}\varepsilon_{11} + \varepsilon_{22} \right)^2 \right)^{\beta_{11}-1} \\ & + \gamma_{11} \left(\frac{1}{2} C_{22}^0 \left(\upsilon_{12}\varepsilon_{11} + \varepsilon_{22} \right)^2 \right) \left(e^{-(\lambda_{11} N)} \right)\end{aligned} \tag{11}$$

$$\begin{aligned}\frac{d(d_{12})}{d(N)} = \frac{d\varphi}{dY_{12}} = {} & \frac{\alpha_{12}\beta_{12}}{1+\beta_{12}} \left(\frac{1}{2} G_{12}^0 \varepsilon_{12}^2 \right)^{\beta_{12}-1} \\ & + \gamma_{12} \left(\frac{1}{2} G_{12}^0 \varepsilon_{12}^2 \right) \left(e^{-(\lambda_{12} N)} \right)\end{aligned} \tag{12}$$

$$\begin{aligned}\frac{d(d_{13})}{d(N)} = \frac{d\varphi}{dY_{13}} = {} & \frac{\alpha_{13}\beta_{13}}{1+\beta_{13}} \left(\frac{1}{2} G_{13}^0 \varepsilon_{13}^2 \right)^{\beta_{13}-1} \\ & + \gamma_{13} \left(\frac{1}{2} G_{13}^0 \varepsilon_{13}^2 \right) \left(e^{-(\lambda_{113} N)} \right)\end{aligned} \tag{13}$$

$$\begin{aligned}\frac{d(d_{23})}{d(N)} = \frac{d\varphi}{dY_{23}} = {} & \frac{\alpha_{23}\beta_{23}}{1+\beta_{23}} \left(\frac{1}{2} G_{23}^0 \varepsilon_{23}^2 \right)^{\beta_{23}-1} \\ & + \gamma_{23} \left(\frac{1}{2} G_{23}^0 \varepsilon_{23}^2 \right) \left(e^{-(\lambda_{23} N)} \right)\end{aligned} \tag{14}$$

The identification procedure is briefly presented in the last section of the present work and will be published in a forthcoming paper.

4 Parametric analysis

A 2D numerical example is presented in this section. It is conducted to asses the applicability of the developed model to predict the damage evolution in a “fictive” generalised material. Nevertheless, the elastic properties data introduced into the FE code are in order of those corresponding to a short glass fibre reinforced thermoplastic (PP or PA-66) composite material. Note that due to the random fibre orientation, the composite behaves as a transverse isotropic media and the FE computation was carried out in the case of 2-D problem.

Table 1. Elastic properties data introduced into the FE code.

E_{11}	E_{22}	G_{12}	V_{12}
4233 MPa	4233 MPa	1385 MPa	0.34

The modelled structure consists of a thin plate having corner shape. The mesh used for the FE computation is obtained as a result of a spatial convergence study. The computed plate is clamped at an extremity and subjected to a normal uniform load at the other one (figure 2).

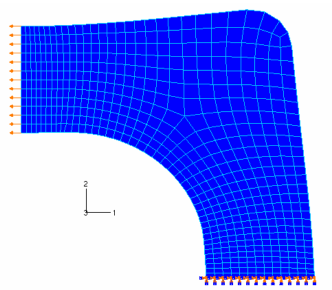

Fig. 2. FE Model of thin corner plate

This geometry allows the validation of the model and numerical implementation in the case of an in-plane stress state. The fatigue computation is conducted as a load-controlled numerical test.

Since the numerical fatigue test is load-controlled the strain will increase as a function of the number of cycles. This mode of control allows showing the three phases of the damage evolution characterising the short glass fibres reinforced thermoplastics.

The damage model parameters have been chosen as given in table 2.

Table 2. Damage parameters used in the MNL model to predict damage evolutions.

α_{11}	α_{22}	α_{12}	β_{11}	β_{22}	β_{12}
0.1	0.1	0.08	4.52	3	3
γ_{11}	γ_{22}	γ_{12}	λ_{11}	λ_{22}	λ_{12}
0.01	0.01	0.01	0.01	0.01	0.01

It should be mentioned that these parameters are fictives. Nevertheless, they allow performing parametric analysis in reasonable computation time.

An example of in plane strains fields (ε_{11}, ε_{22}, ε_{12}) and spatial repartitions of the in-plane damage variables (d_{11}, d_{22}, d_{12}) predicted by the model MNL is shown in figure 3.

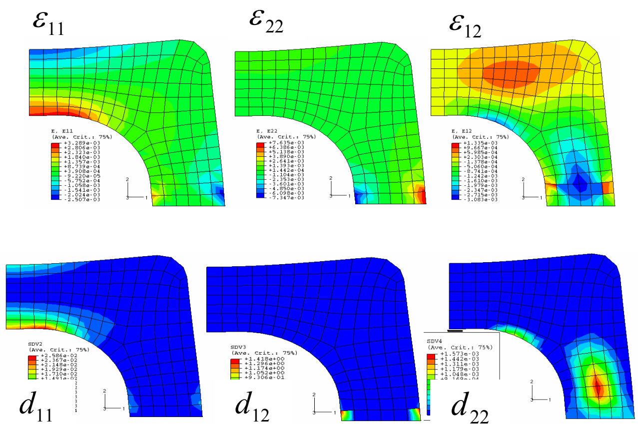

Fig. 3. Example of numerical results computed using the MNL implemented model at an increment corresponding to a number of cycles N = 1600 cycles

A parametric study is also performed in order to emphasize and to understand the effect of material parameters on the damage kinetic and accumulation under cyclic loading. For sake of simplicity, the sensitivity analysis is carried-out upon the longitudinal direction. Hence, only the longitudinal damage variable (d_{11}) is presented

It should be noticed that for the sensitivity analysis, when one of the parameters is varying, the others are kept constants. Note that nominal values of the damage parameters are: α = 0.1, β=4.52, λ=0.01 and γ=0.01.

As shown in figure 4, one notices that when the (γ) parameter increases, the first stage of the damage becomes less significant. Consequently, rather than a rapid increase of damage evolution, one observes a gradual and a steady damage evolution during the first hundred loading cycles. Therefore, the first stage is more akin to the second damage stage and both stages can be confounded.

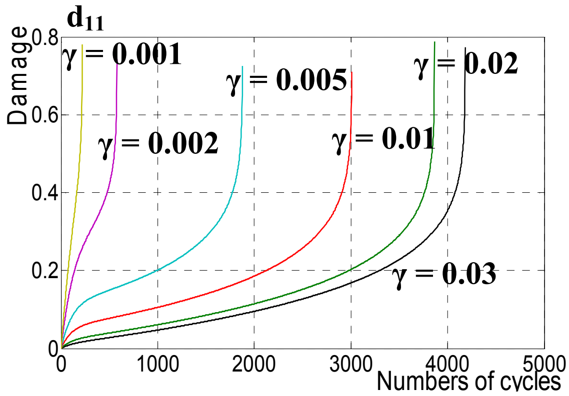

Fig. 4. Effet of the the parameter (γ) on the evolution of the damage variable (d_{11}).

Finally, one notices that the increase of the parameter (γ) leads to an increase of the number of cycles prior the third damage stage. Thus, a short glass fibres reinforced thermoplastic whose (γ) parameter is high will exhibits a damage kinetic similar to that characterising a unidirectional composite with thermoset matrix [4-5].

Furthermore, it is easy to show that a decrease of the (γ) parameter will lead to damage kinetics more governed by the first stage of damage. As expected, damage occurs according to an unstable and rapid increase. Accordingly, the second stage is almost non-existent and the third stage is reached for a low number of cycles.

As shown in figure 5, the variation of the parameter (λ) may also modify the damage kinetic. Indeed, by increasing this parameter the damage evolution is more accelerated and may lead to a rapid total degradation. One can notice that the increase of the parameter (λ) will have similar consequence than the decrease of the parameter (γ). Moreover, according to the developed model a composite material with a low parameter (λ) will exhibit a reduced first stage of damage and then a progressive degradation till the final stage. The material reaches the total failure for a relatively high number of loading cycles.

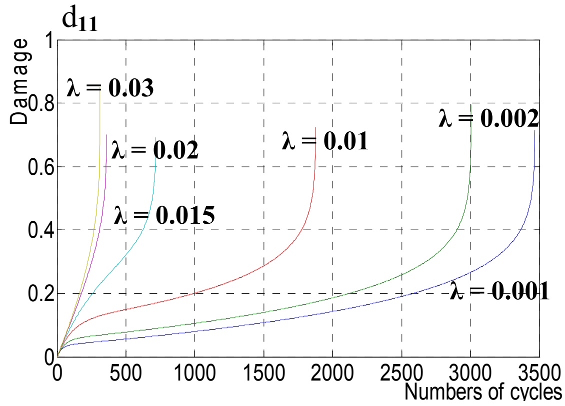

Fig. 5. Sensitivity of the damage evolution variable (d_{11}) to the parameter (λ)

The parameter (β) has also an important influence on the damage kinetic. In fact, as illustrated in figure 6, the parameter (β) controls the slope of the second stage of damage evolution (linear stage). For instance, to reach a longitudinal modulus reduction of 1% (d_{11}= 0.01) a material having parameter (β=5.52) requires 1000 cycles whereas another material characterised by a β=6.52 goes till 10000 cycles. It is obvious hence that by increasing the parameter (β) one can improve the damage fatigue life.

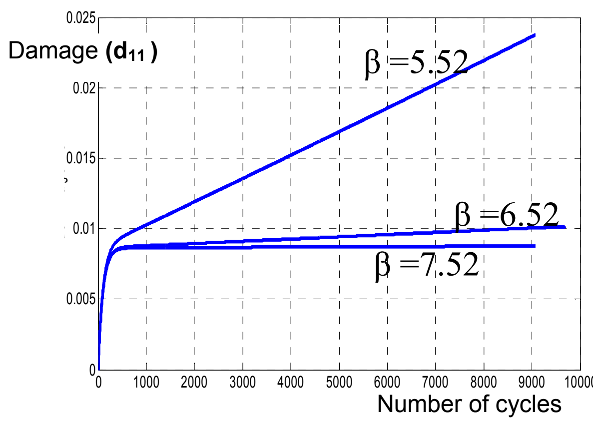

Fig. 6. Sensitivity of the damage *variable (d_{11})* evolution to the parameter (β)

For the parameter (α) figure 7 shows that by increasing this damage parameter one obtains comparable effects to a decrease of the parameter (β). As expected, both damage parameter (α and β) have negligible effects, if any, on the first damage stage but govern the beginning of the third one. This claim can be easily explained by the new dissipation formulation given by the equation (8).

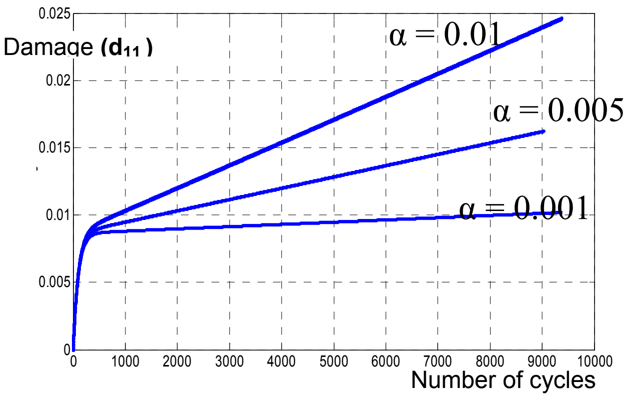

Fig. 7. Sensitivity of the damage evolution *variable* *(d_{11})* to the parameter (α)

The performed parametric study shed light on the relations between the damage accumulation and the characteristic material parameters. A variation of the (λ) and (γ) parameters governs mainly the first and the second damage stages. Both parameters can accelerate or delay the final damage state and hence increase or decrease the total loading cycles Parameters (β) and (α) have a large influence on the damage rate (slope) of the second stage and the onset level of the third one.

The parametric analysis is useful since it allows optimising the experimental procedure aimed at identifying the material parameters. Indeed, as a result of this parametric study it is obvious that the best identifiability of both parameters (λ and γ) will be obtained during the first damage stage namely for the few thousands first cycles. the (β) and (α) parameters will be identified during the second and the third stages of damage accumulation.

4. Identification of the damage model parameters

Experimental implementation and validation of the MNL model is currently in progress. It deals with the identification of the damaged behaviour law parameters using optical whole-field strain measurements coupled to an inverse method [11-12]. This identification will allow reaching simultaneously all of the parameters governing the behaviour law. It is worth noting that experimental tests must give rise to heterogeneous strain/stress fields. Indeed, in this case, the constitutive parameters are expected to be all involved in the response of the specimen. Therefore, intrinsic behaviour constants can potentially be extracted through an identification strategy using kinematics fields obtained from one single coupon. The main objective of inverse methods is the determination of a selected set of unknown parameters. Starting from an initial guess values, these unknown parameters are estimated iteratively by comparing experimentally measured with numerically computed quantities displacement. The ultimate goal of the proposed approach is to determine the unknowns fatigue damage material parameters of an anisotropic material on the basis of a heterogeneous strains fields experimental configuration. Figure 8 shows the general identification flow-charts.

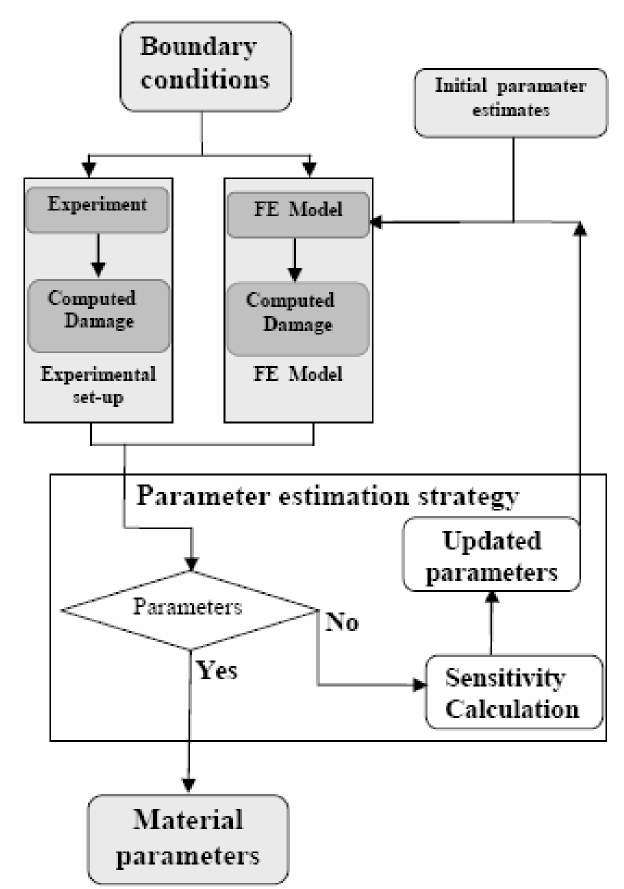

Fig. 8. Flow-chart of the inverse method for material parameter identification

5 Conclusion

A phenomenological modelling of fatigue damage in short glass fibre reinforced thermoplastic matrix composites was developed and implemented into ABAQUS FE code. The implementation of the MNL model allowed predicting accurately the damage evolution. A new dissipation potential function was proposed and introduced into the framework of continuum damage mechanics to capture the damage kinetic specific to short glass fibre reinforced thermoplastics. The latter is characterised by an evolution of the damage in three stages. The new MNL model is thus able to take into account the first stage of damage specific to the composite materials with thermoplastic matrix (figures 9 and 10). A Numerical example was studied to demonstrate the application of the proposed damage model for composite materials subjected to cyclic loading and to conduct parametric and sensitivity studies. It has been demonstrated that a variation of the (λ) and (γ) parameters governs mainly the first and the second damage stages. Both parameters (β) and (α) have a large influence on the damage rate (slope) of the second stage and the onset level of the third one.

The parametric analysis is useful since it allows optimising the ongoing experimental procedure aimed at identifying the material parameters. This procedure will use optical whole-field strain measurements coupled to an inverse method and will allow reaching simultaneously all of the parameters governing the behaviour law.

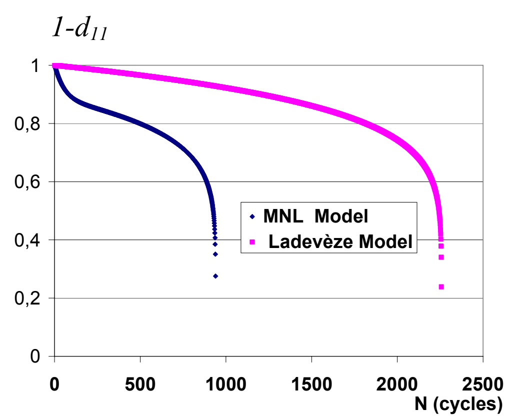

Fig. 9. Comparison between longitudinal modulus reduction evolutions ($1-d_{11}$) predicted by Ladevèze and the MNL models.

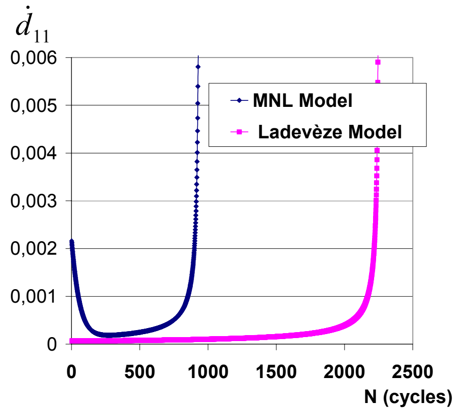

Fig. 10. Comparision of the damage rate $\dot{d}_{11} = \frac{\partial \varphi}{\partial Y_{11}} = \frac{\partial d_{11}}{\partial N}$ evolution predicted by Ladevèze and MNL models.

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