Fatigue damage modelling of PEEK short fibre composites

A. Avanzini, G. Donzella, D. Gallina*

University of Brescia, via Branze 38, Brescia 25123, Italy

Abstract

In the present research the fatigue damage evolution of a PEEK based composite was studied. Examined material consisted of a PEEK matrix reinforced by carbon micro-fibres with addition of fillers such as graphite and PTFE. Fatigue tests in load control were carried out up to 10^6 cycles at different stress level, with cycle ratio R=0 and frequency 10 Hz. The damage evolution was evaluated by defining damage parameter based on elastic modulus reduction observed under cyclic loading. The cyclic damage evolution of PEEK based composite, which is a function of applied stress level, presented significantly different damage stages. In order to reproduce fatigue damage kinetic observed experimentally a phenomenological modelling approach was then implemented into a finite element code, based on fatigue damage model recently proposed for short fibre reinforced thermoplastic composites.

© 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of ICM11

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Short fibers composite materials are extensively used in numerous industrial fields, such as aerospace, automotive and biomedical, because of their high specific stiffness and strength.

| Nomenclature |
|---------------|
| d | Damage state variable |

* Corresponding author. Tel.: +39-030-371-5807; fax: +39-030-370-2448.
E-mail address: davide.gallina@ing.unibs.it.
Fatigue tests in load control were carried out up to 10^6 cycles at different stress level, with cycle ratio R=0 and 1.

Keywords: © 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of ICM11

In the present research the fatigue damage evolution of a PEEK based composite was studied. Examined material consisted of a PEEK matrix reinforced by carbon micro-fibres with addition of fillers such as graphite and PTFE.

In order to model this kind of fatigue damage evolution, an original approach has been recently developed by Nouri at al. [2]. This model, which includes anisotropy effects, has been built in the framework of the continuum damage mechanics using an incremental description of the anisotropic damage kinetics. Differently to other models [3] this model has been formulated in the strain space, thus making easier the numerical implementation, such as in a finite element (FE) code, compared to a stress formulation. In the present work fatigue damage evolution of short-fiber reinforced PEEK based composite was investigated experimentally by carrying out tests at different stress levels and obtaining damage evolution as a function of cycle number. Then a cyclic damage modeling approach based on the work of Nouri has been adopted, with some modifications, to predict the fatigue damage evolution observed experimentally and a damage model has been implemented into commercial FE code Abaqus® customizing user subroutine USDFLD.

2. Experimental

Fatigue damage evolution has been studied for a short fiber reinforced polyether-ether-ketone (PEEK), filled with 10% weight fraction of carbon micro-fiber, graphite and PTFE, referred to as PVX in the following. It is mainly employed in applications in which tribological aspects are of interest, due to action of PTFE and graphite as internal lubricants. Dog-bone shaped specimens used in fatigue tests were cut from semi-finished 6 mm thick plates along the extrusion direction (supplier Ensinger® Italia). In thermoplastic composites obtained by injection or extrusion molding the presence of a layered skin-core structure [6] has been reported. The distribution of fibers was therefore examined at optical microscope

| Symbol | Description                       |
|--------|----------------------------------|
| W_d    | Strain energy of damaged material |
| Y      | Thermodynamic dual forces        |

These materials are increasingly employed for structural applications in which they are subjected to cyclic loading. Damage accumulation resulting from loading may then lead to component failure due to excessive degradation of material properties. It is therefore important to carefully evaluate the damage and material properties evolution under cyclic loading condition. This kind of investigation usually involves expensive and time consuming experimental campaign, in particular when heterogeneous materials like short fiber reinforced composites are considered since different failure and damage mechanisms may be present. Hence, it is obviously important to develop models able to predict the fatigue behavior of composite materials that may help to reduce this experimental effort to selected tests. Ideally the fatigue damage model should be versatile as much as possible and not too complex in terms of material parameters to be determined for its practical application. Fatigue damage evolution in fiber-reinforced composite materials is a quite complex phenomenon, especially in terms of onset and evolution, and a large research effort has been spent on it up to now [1-5]. Indeed, composite materials are subjected to different types of damage that may interact. The micro-mechanisms of damage accumulation occur sometimes independently and interactively, and the predominance of one and other of them may be strongly affected by both material variables and testing conditions. In particular, for some short fiber reinforced composite materials, like polyamide reinforced with short glass fibers, fatigue damage evolution under cyclic loading has been observed to occur according to three stages:

- Stage 1: matrix micro-cracks and matrix micro-voids (high stiffness reduction, material softening)
- Stage 2: coalescence and propagation of defects (gradual material stiffness reduction)
- Stage 3: macroscopic crack propagation and fiber fracture (fast stiffness reduction)

These materials are increasingly employed for structural applications in which they are subjected to cyclic loading. Damage accumulation resulting from loading may then lead to component failure due to excessive degradation of material properties. It is therefore important to carefully evaluate the damage and material properties evolution under cyclic loading condition. This kind of investigation usually involves expensive and time consuming experimental campaign, in particular when heterogeneous materials like short fiber reinforced composites are considered since different failure and damage mechanisms may be present. Hence, it is obviously important to develop models able to predict the fatigue behavior of composite materials that may help to reduce this experimental effort to selected tests. Ideally the fatigue damage model should be versatile as much as possible and not too complex in terms of material parameters to be determined for its practical application. Fatigue damage evolution in fiber-reinforced composite materials is a quite complex phenomenon, especially in terms of onset and evolution, and a large research effort has been spent on it up to now [1-5]. Indeed, composite materials are subjected to different types of damage that may interact. The micro-mechanisms of damage accumulation occur sometimes independently and interactively, and the predominance of one and other of them may be strongly affected by both material variables and testing conditions. In particular, for some short fiber reinforced composite materials, like polyamide reinforced with short glass fibers, fatigue damage evolution under cyclic loading has been observed to occur according to three stages:
on transversal sections with respect to specimen main axis. Results indicate that for PVX fibers distribution in the gauge region of the specimen tested do not seem to present such a layered distribution; this obviously influences significantly the properties of the material. In order to evaluate the damage evolution uni-axial fatigue tests were carried-out. Tests were run in load control mode by applying sinusoidal tensile load of constant amplitude on a servo-hydraulic testing machine Instron 8501 equipped with an infrared pyrometer in order to monitor the specimen surface temperature. Tests were run up to $10^6$ cycles, or up to specimen failure, keeping the load ratio $R = (\text{min. load}/\text{max. load})$ equal to zero and the cyclic frequency equal to 10 Hz. This frequency allowed obtaining reasonable test duration without excessive increase of the specimen temperature due to hysteretic effect. During the tests minimum and maximum axial strain values were recorded for each cycle, while full stress-strain hysteresis cycles were recorded at fixed time intervals.

3. Damage modeling approach

In parallel to experimental testing a numerical model was developed to simulate damage evolution observed experimentally. In particular the model proposed by Nouri et al. [2] for the prediction of cyclic damage evolution for short glass fiber reinforced polyamides has been taken as a reference to implement a similar approach for damage modeling of short fiber reinforced PEEK. In the following some key points of this model will be recalled to help discussion of model application to PEEK based composites as proposed in the present work. For a detailed description of the model the reader may refer to Nouri work [2] and Ladeveze [3]. In this model the response of the undamaged material is assumed to be orthotropic linearly elastic and the damage is assumed to be diffuse. Nouri et al. formulated their model in the strain space, making it easier the numerical implementation then the stress formulation. Strain energy of the damaged material, denoted by $W_d$, is then defined as a function of the strain tensor ($\varepsilon_{ij}$):

$$
2W_d = \frac{1}{1 - v_{ij}} \left[ E_{ij}^0 (1 - d_{ij}) \varepsilon_{ij} (\varepsilon_{ij} + v_{2ij} \varepsilon_{2ij}) + E_{ij}^0 (1 - v_{ij} \varepsilon_{ij}) \varepsilon_{ij} \right] + \frac{1}{1 - v_{ij}} \left[ G_{ij}^0 (1 - d_{ij}) \varepsilon_{ij} + G_{ij}^0 (1 - v_{ij} \varepsilon_{ij}) \varepsilon_{ij} \right] + G_{ij}^0 (1 - d_{ij}) \varepsilon_{ij} + G_{ij}^0 (1 - v_{ij} \varepsilon_{ij}) \varepsilon_{ij} + \gamma_{ij} \varepsilon_{ij}^3
$$

where $E_{ij}^0$ (with $i = j, \ 1,2$) and $G_{ij}^0$ (with $i \neq j, \ 1,2,3$) are the elastic moduli of the material in the undamaged state; $d_{ij}$ represents the damage, so that the elastic properties of the damaged material are:

$$
E_{ij} = E_{ij}^0 (1 - d_{ij}) \quad G_{ij} = G_{ij}^0 (1 - d_{ij})
$$

Damage rate are then derived by equations having the following form:

$$
\frac{\partial d_{ij}}{\partial N} = \dot{d}_{ij} = \frac{\alpha}{1 + \beta} \left( Y_{ij}^{\delta,\gamma} \right)^{1/\gamma} + \lambda_{ij} \left( Y_{ij}^{\delta,\gamma} \right)^{1/\gamma} + \mu_{ij} \left( Y_{ij}^{\delta,\gamma} \right)^{1/\gamma}
$$

where $\alpha, \beta, \delta$ and $\gamma$ are the material damage constants along different directions and $Y_{ij}$ are thermodynamic dual forces associated with the damage rates $\partial d/\partial N$. The damage variables $d_{ij}$ are obtained by integration of equations (3), with initial conditions $d_{ij}(N=0) = d_{\text{static}}$. In the present work a similar approach has been adopted but introducing some modifications to take into account the characteristics of the material examined and the test procedure. In particular the material did not exhibit a marked anisotropy as also indicated by random distribution of short fibers orientation. Therefore the
orthotropic model proposed by Nouri may be simplified by considering only one damage state variable $d$ representing the stiffness reduction during cyclic loading. The strain energy for the damaged material may then be written as follows:

$$2W_d = \frac{E^0}{1 - v^2} \left[ \varepsilon_{11} \left( \varepsilon_{11} + \nu \varepsilon_{22} \right) + \varepsilon_{22} \left( \varepsilon_{22} + \nu \varepsilon_{11} \right) \right] + \frac{E^0}{1 - v^2} \left[ \varepsilon_{11} \left( \varepsilon_{11} + \nu \varepsilon_{22} \right) + \varepsilon_{22} \left( \varepsilon_{22} + \nu \varepsilon_{11} \right) \right] + \frac{E^0}{2(1 + v)} \gamma_{12}^2$$

(4)

The thermodynamic dual variable $Y$ is then defined as:

$$Y = \frac{E^0}{2(1 - v^2)} \left[ \varepsilon_{11} \left( \varepsilon_{11} + \nu \varepsilon_{22} \right) + \varepsilon_{22} \left( \varepsilon_{22} + \nu \varepsilon_{11} \right) \right] + \frac{E^0}{4(1 + v)} \gamma_{12}^2$$

(5)

Having defined $Y$, in order to obtain the damage variable $d_{ij}$, for strain controlled tests it would possible to integrate directly the damage rate $\partial d/\partial N$. However, for stress controlled tests, strain continuously changes and therefore direct integration of the damage rates $\partial d/\partial N$ is not possible. It would then be necessary to integrate numerically over any loading cycle. Since a fatigue test may consist of thousands of cycles, this would bring about an exponential increase in the processing time needed for calculations. In order to avoid these time consuming integration problems, related to stress controlled tests, a direct definition of damage was assumed. In particular a damage state variable $d$, able to correctly describe the damage evolution of PVX, has been defined as a function of the thermodynamic force $Y$ as follows:

$$d = \alpha \ln(N) \cdot Y^{\beta - 1}$$

(6)

The logarithmic factor $\ln(N)$ describes the first stiffness reduction due to material softening and the second factor is used to control the curves trend at different levels of applied stress. Coefficients $\alpha$ and $\beta$ are the material damage constants. Thanks to the fact that the model formulation is written in the strain field, making easy the numerical implementation, the presented damage model has been numerically implemented into the finite element (FE) code Abaqus® in order to predict the fatigue damaged behavior of PVX observed during experimental tests. Damage model has been implemented customizing user subroutine USDFLD.

4. Results and discussion

4.1. Fatigue tests

Fatigue life curve of PVX is reported in Fig. 1a in which maximum applied fatigue stress ($\sigma_{max}$) is plotted against numbers of cycles to failure ($N_f$). Fatigue life charts include run-out (tests stopped after $10^6$ cycles). During fatigue tests temperature was monitored by means of a pyrometer. For low stress level tests PVX temperature increase was in the range from 5°C to 20°C respect to initial room temperature and material reached thermal equilibrium. At high stress level a slightly higher increase was observed but without stabilization. However failure mechanism appeared to be similar and no thermal failures were observed. Temperature increase may significantly influence the mechanical properties of the material, however, also basing on these experimental observations, temperature effects were not included in the damage model. For quantitative evaluation of fatigue damage, Young’s modulus or composite material stiffness are used [1]. Coherently with damage modeling approach, experimental fatigue damage $D$ was simply defined as per eq. (2) deriving $E_0$ and $E$ from cyclic ratio $\Delta \sigma / \Delta \varepsilon$. Fatigue damage evolution of PVX is showed in Fig.1b. Even at low stress level and even if temperature reached a stable value, the damage...
index did not tend to stabilize completely, also for specimen that reached $10^6$ cycles. Damage curve shape depends on stress level, with a higher slope at high stress level, whereas at lower stress level the damage rate appears to be slightly higher in the initial stage followed by a stage in which slope of D-N decreases. Although D is basically a phenomenological parameter, these differences observed on a macroscopical level suggest that different fatigue damage mechanisms may be present depending on applied stress level. Under a damage modeling point of view a model able to reproduce different evolution of damage as a function of stress level is therefore needed to accurately predict damage accumulation.

![Fatigue life curve and damage evolution](image)

**Fig. 1.** (a) fatigue life curve; (b) damage evolution of PVX at different stress levels

### 4.2. Damage modeling

Basing on experimental results a fitting procedure was applied to determine damage parameters to be introduced in the model to describe material damage. The equation defining the damage model previously described were implemented into an electronic calculation sheet. The fitting procedure was applied to experimental damage curves corresponding to different imposed stress levels and values of $\alpha = 0.019$ and $\beta = 1.77$ were found to allow a satisfactory matching between experimental and analytical prediction. Then the damage model was implemented into the FEM code Abaqus® by customizing user subroutine USDFLD which allows defining field variables at a material point as a function of time or of any available material point quantities and it can be used to introduce solution-dependent material properties defined as functions of field variables. The numerical simulation allows obtaining the strain field related to the maximum stress value reached during the general fatigue cycle. At every cycle, these values are used by the subroutine to evaluate the thermodynamic dual variable $Y$ and then the correspondent damage state variable $d$ which is used by the program to update the composite material properties to use in the next cycle. The procedure carries on until a selected number of cycles or a predefined limit value of the damage is reached. The outputs of the FE analysis are the fatigue damage value $d$ and the stress at each cycle expressed at the Gauss point. In particular the damage model previously described was implemented in the code to simulate damage accumulation during tension-tension uni-axial fatigue tests. The FE model consists of a 3D dumb-bell specimen with dimensions and shape equal to real specimen. Boundary conditions consisted in clamping the specimen at an extremity and applying a longitudinal cyclic load at the other one, with a load ratio $R=0$. The mesh used to discretize the model is obtained from a convergence study and 136 elements have been used. Results from finite elements analyses then allowed evaluation of the strain field $\varepsilon$ and, by means of the subroutine, of the diffuse damage variable $d$ predicted by the developed damage model. As an example the progressive evolution of predicted damage during the simulation of a test with a longitudinal applied stress equal to 61 MPa is shown in Fig.2a. Then
the damage predicted by means of the FEM model were compared, at different stress levels, with the actual damage evolution obtained from experimental tests, as shown in Fig. 2b. Despite some simplifying assumption concerning the isotropic nature of PEEK composite studied and direct definition of damage variable as per eq. (6), overall it may be observed that the numerical model allowed a satisfactory prediction of the damage evolution of PVX at each of the different stress levels considered.

Fig. 2. (a) damage distribution in the specimen; (b) comparison of experimental and simulated behavior at different stress levels

5. Conclusion

An isotropic fatigue damage accumulation model for a PEEK based short fiber reinforced composite material has been proposed in this paper. The model is based on some recent work of fatigue damage modeling for short fiber reinforced composites [2], modified to take into account some specific features of PEEK mechanical behavior experimentally observed. The model, formulated in the strain space and based on the definition of damage variables as a function of thermodynamic dual forces, includes some simplifying assumptions to reduce computational effort. Basing on experimental data material parameters to be introduced in the damage law were determined and numerical implementation into the Abaqus FE code was carried out. The implementation of the damage model allowed predicting the fatigue damage evolution in a PEEK short fiber composite at different applied stress with good agreement between the damage predicted by the model and the experimental damage observed.

References

[1] Mao H, Mahadevan S. Fatigue damage modelling of composite materials. Composite Structures 2002;58:405-410.
[2] Nouri H, Meraghni F, Lory P. Fatigue damage model for injection-molded short glass fibre reinforced thermoplastics. International Journal of Fatigue 2009;31:934-942.
[3] Ladeveze P, Le Dantec E. Damage modelling of the elementary ply for laminated composites. Composites Science and Technology 1992;43:257-267.
[4] Chen HS, Hwang SF. A fatigue damage model for composite materials. Polymers Composites 2009;30:301-308.
[5] Lee CS, Hwang W. Fatigue life prediction of matrix dominated polymer composite materials. Polymer Composites 2000;21:798-805.
[6] Saib KS, Isaac DH, Evans WJ. Effects of processing variables on fatigue in molded PEEK and its short fiber composites. Materials and Manufacturing Processes 1994;9:829-850.