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A Material Model for Prediction of Fatigue Damage and Degradation of CFRP Materials

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Abstract. Objective of the present study is the definition of a material model accounting for fatigue damage and degradation. The model is formulated as a brittle damage model in the otherwise linear elastic framework. A stress driven damage evolution equation is derived from microplasticity considerations. The model is implemented as a user-defined material model into a commercial finite element program. In a comparison with experimental data in the low cycle fatigue regime, a good agreement with the numerical prediction is obtained.

Introduction

Fatigue damage is a major concern restricting the lifetime of almost all engineering materials. Carbon fiber reinforced plastics (CFRP) are no exception, although they are in many cases more resistant to fatigue than metallic materials. On the other hand, CFRP materials exhibit some specific features, requiring a special consideration in the numerical modelling of this effect. One of the special characteristics is the successive material degradation which may occur from the initial loading period onwards, resulting in a sometimes significant (but confined) decrease in their stiffness in the initial range of fatigue loading, followed by a period with small or negligible stiffness and strength degradation as well as a rapidly increasing degradation till failure in the final cyclic loading range (e.g. [1], [6], see also Fig. 1). The initial degradation is caused by the formation of micro cracks at local stress concentrations within the microstructure during the first loading cycles. Due to the microstructural anisotropy of the material, the degradation effect is also anisotropic. When the material is employed in the form of laminates of different unidirectionally fiber reinforced plies with different fiber orientation, the degradation effect in the initial loading range may result in a non-negligible stress and strain re-distribution compared to the laminate in as-received conditions.

Material model

General assumptions. In order to be able to deal with the fatigue degradation and stress re-distribution effects in structures consisting of laminated CFRP materials mentioned in Sec. 1, a damage material model accounting for the fatigue-related stiffness degradation is required. For an efficient numerical analysis in the engineering sense, this model is required to be as simple as possible. Nevertheless, it has to be able to capture all essential effects. The model is derived under the following assumptions [3], [4]:

- the basic stress-strain response is approximately linear elastic till failure and thus can be described by using Hooke's law in the anisotropic form,
- the anisotropic damage effects are caused by micro crack formation within the microstructure,

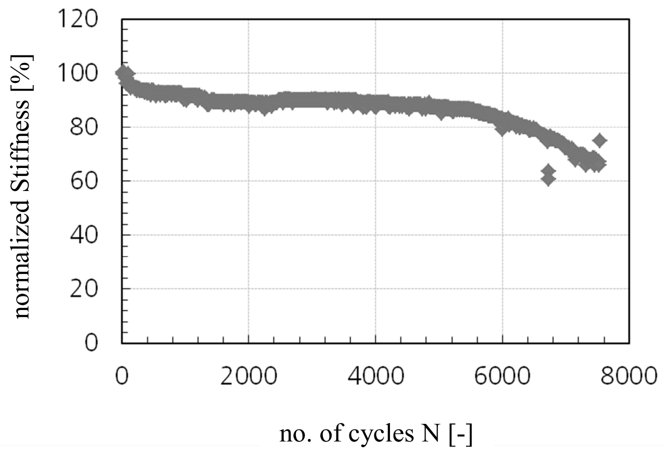


Fig. 1: Stiffness degradation due to fatigue.

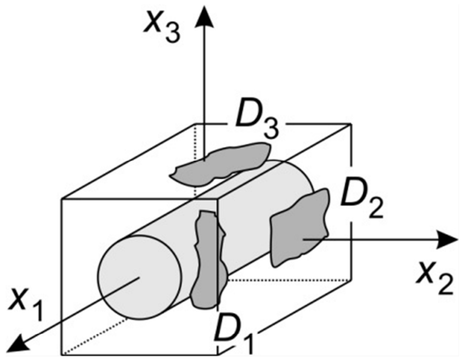


Fig. 2: Anisotropic damage variables.

- the effect of the micro crack formation on the material response can be described in the Lemaitre-Kachanov sense by scaling

$$\bar{\sigma} = (1 - D)\sigma \tag{1}$$

of the stresses using three independent damage variables Di, i = 1, 2, 3 related to the coordinate directions according to Fig. 2,

- the evolution of the damage variables is controlled by micro-plastic effects, where micro-plasticity is defined as plasticity occurring below the macroscopic yield limit.

Mathematical formulation. Considering the basic assumptions made in the previous section, the stress-strain-response of the material can be described by

$$\begin{pmatrix} \bar{\varepsilon}_{11} \\ \bar{\varepsilon}_{22} \\ \bar{\varepsilon}_{33} \\ 2\bar{\varepsilon}_{23} \\ 2\bar{\varepsilon}_{13} \\ 2\bar{\varepsilon}_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{(1-D_1)E_1} & -\frac{\upsilon_{21}}{E_2} & -\frac{\upsilon_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{E_1} & \frac{1}{(1-D_2)E_2} & -\frac{\upsilon_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\upsilon_{13}}{E_1} & -\frac{\upsilon_{23}}{E_2} & \frac{1}{(1-D_3)E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-D_2)(1-D_3)G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-D_1)(1-D_3)G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-D_1)(1-D_2)G_{12}} \end{pmatrix} \begin{pmatrix} \bar{\sigma}_{11} \\ \bar{\sigma}_{22} \\ \bar{\sigma}_{33} \\ \bar{\sigma}_{23} \\ \bar{\sigma}_{13} \\ \bar{\sigma}_{12} \end{pmatrix} \tag{2}$$

where E_i, G_i and ν_{ij} are the engineering constants of the material in the as-received state. Notice that even in the case that the material were transversally isotropic in the as-received state, the transversal isotropy might be lost during the development of fatigue damage. Since the damage effects under tensile and compressive deformation in general will be different, different damage variables D_i^{t} and D_i^{c} are introduced for tensile and compressive stress states, respectively.

Assuming that the evolution dD of damage is related to the evolution dw^{mp} of micro-plastic work and that the micro-plastic deformation can be described by the Ramberg-Osgood equation, the damage evolution can be described by

$$\mathrm{d}D = \begin{cases} A\, w(D) \,|\, \bar{\sigma} \,|^{n} \, \mathrm{d}\sigma & \text{for :} \quad \mathrm{d}\bar{\sigma} > 0 \\ 0 & \text{for :} \quad \mathrm{d}\bar{\sigma} \le 0 \end{cases} \tag{3}$$

where A and n are material parameters. The warping function $w(D)$ is defined such that for small and large damage states a rapid (initial and final) damage evolution is obtained whereas only limited damage evolutions are obtained at intermediate damage states. By this means, the previous version [3], [4] of the model is reformulated to a pure stress based formulation of the damage evolution.

In this context, since the micro-plastic deformations below the macroscopic yield limit are in general much smaller than the elastic strains, the micro-plastic strains can efficiently be estimated from the corresponding elastic strains. Due to the anisotropy of the damage process and the independent treatment of the damage evolution under tensile and compressive stress states, a total of six independent damage evolution equations of the type (3) are introduced for the six independent damage variables D_i^{t} and D_i^{c}.

Finite element implementation. The damage model (2) and (3) as sketched in the previous section is implemented as a user-defined material model into a commercial finite element system [2]. For this purpose, in the temporal discretization, the damage evolution (3) is approximated by means of a backward Euler scheme. The corresponding nonlinear system of equations for the stress components σ_{ij} and the damage increments $\mathrm{d}D_i^{\mathrm{t}}$ and $\mathrm{d}D_i^{\mathrm{c}}$ is solved numerically using Newton's method. In order to increase the numerical stability of the computation in the case of complete damage of individual elements, an artificial gradual decrease of the damage evolutions $\mathrm{d}D_i^{\mathrm{t}}$ and $\mathrm{d}D_i^{\mathrm{c}}$ down to zero damage evolution $\mathrm{d}D = 0$ for damage states in the range $D = 0.85, \ldots, 0.95$ is introduced, replacing the penalty formulation used in the initial formulation [3], [4] of the proposed fatigue damage model.

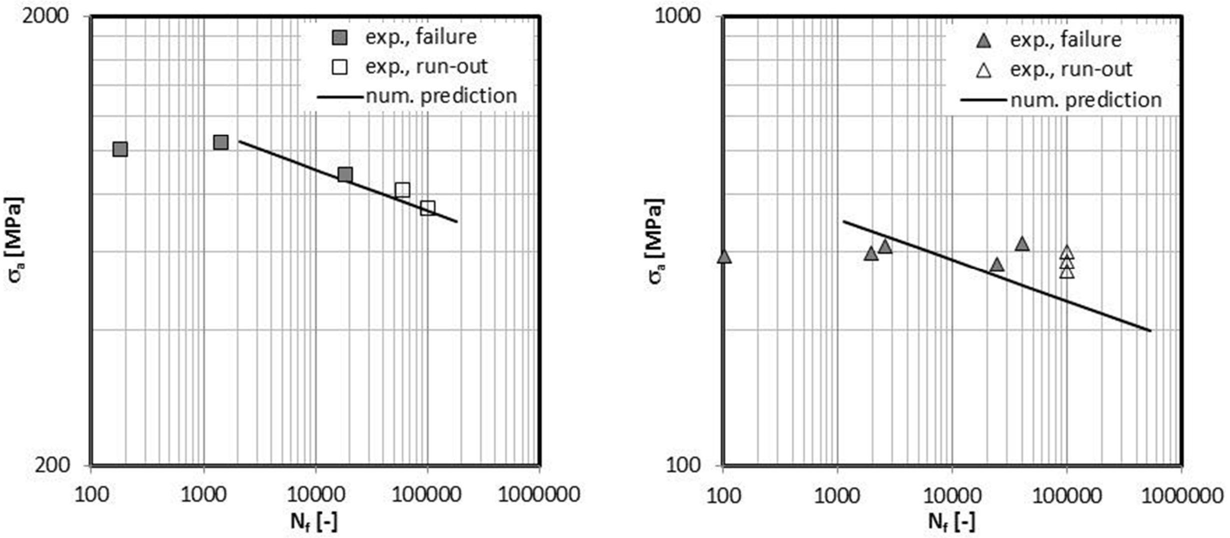
Example

As a numerical example for validation of the proposed model, the model is applied to an experimental data base obtained on a filament wound carbon fiber reinforced epoxy matrix material [3]. The material has been tested experimentally in the low cycle fatigue range under tension and compression with load ratios of $R = 0.1$ and $R = 10$, respectively. Both, loading within the fiber direction and perpendicular to the fiber direction have been applied. Experiments resulting in a number of load cycles in excess of $N = 100\,000$ were considered as run-outs. The cyclic experiments have been complemented by corresponding quasi-static tests under proportional loading till failure for determination of the elastic constants E_i, G_i and ν_{ij}.

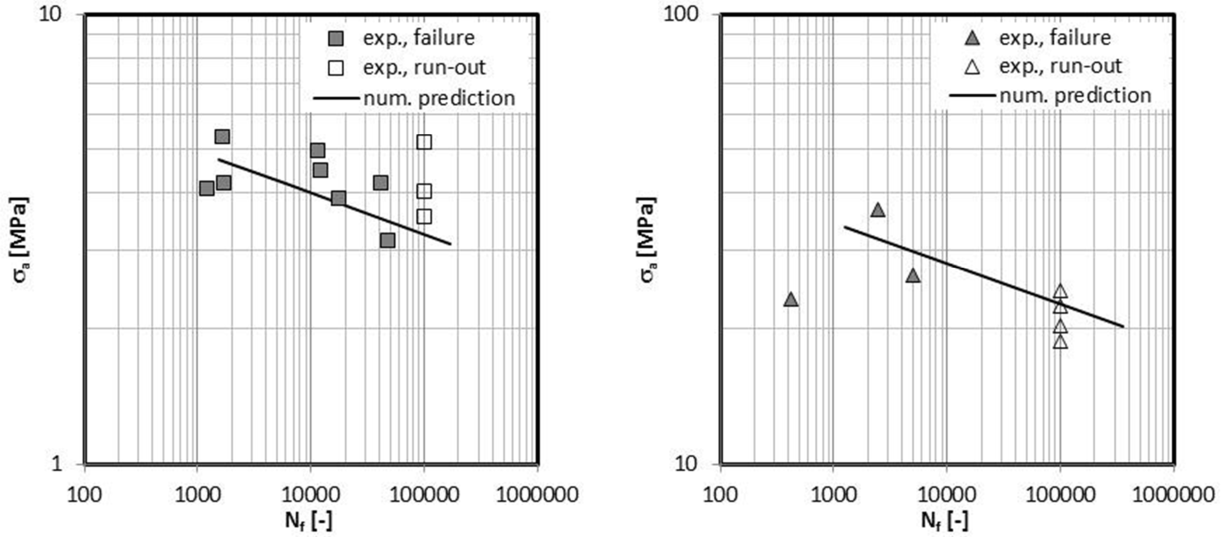
The damage evolution parameters A and n for the different damage evolution equations were determined by means of a numerical simulation of the respective experiments in conjunction with a reversed engineering approach. The results are presented in Fig. 3. The experimental results and the numerical predictions are found in a good agreement for all load cases considered. In all cases, the proposed fatigue damage model is able to adequately predict the functional form of the S-N-curves as straight lines in the $\log \sigma - \log \mathrm{N}$ diagrams. The slope and the position of the *S-N*-curves are obtained by an appropriate choice of the material parameters n and A in the damage evolution equations. A comparison with other data from literature (e.g. [5]) yields identical results.

Conclusion

The present study is concerned with the development and numerical implementation of a continuum damage model for prediction of the fatigue degradation of CFRP materials. The model is based on linear elasticity in conjunction with anisotropic damage, assumed to be controlled by the micro-plastic work below the macroscopic yield limit. The model is implemented as a user defined material model into a commercial finite element code. In a validation against experimental data, the model proves to be both, accurate and numerically efficient. The main advantage of the proposed model is that the damage evolution is related directly to the evolution in the micro-plastic work in the individual time increments. Hence, the model accounts for varying amplitudes in a natural manner. Due to the estimation of the micro-plastic work from the elastic strains, the model is numerically efficient since it avoids the iterative accumulation of micro-plastic strains.



(a) tensile fatigue load within fiber direction (b) compressive load within fiber direction



(c) tensile load perpendicular to fiber direction (d) compressive load perpendicular to fibers

Fig. 3: Validation against experimental data.

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