A FATIGUE DAMAGE DEGRADATION MODEL FOR CFRP MATERIALS

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1. Introduction

Carbon fiber reinforced plastics (CFRP) are common materials in all fields of lightweight construction. In addition to the classical field of aerospace, CFRP materials nowadays are widely used in automotive industry and other fields of the transport sector, the naval industry, in the wind energy industry as well as in nonclassical fields of lightweight construction such as civil engineering. A major concern under cyclic loading is the fatigue resistance. A special feature for fiber reinforced materials is the initial stiffness degradation at low cycle numbers followed by a region of nearly vanishing degradation until a progressive material degradation till failure occurs towards the end of the fatigue lifetime. Objective of the present study is the formulation, implementation and validation of an anisotropic continuum damage model for CFRP materials accounting for these effects.

2. Formulation

Using a generalization of an earlier approach (Gauch [1], Hohe et al. [2]), the model is based on the following basic assumptions:

- except for damage effects, the material response is linear elastic as described by Hooke's law,
- the anisotropic damage mechanism is the formation, growth and coalescence of microcracks oriented towards the three main spatial directions,
- the damage evolution is controlled by the dissipation of microplastic work below the overall yield limit of the material.

Considering these basic assumptions and employing a Kachanov-Lemaitre type damage approach

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

by scaling of the stress σ determined from the material constitutive equation with a damage variable D, defined with respect to the different spatial directions, the constitutive equation

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

is obtained, where E_i, G_{ij} and ν_{ij} are the anisotropic elastic constants whereas D_i are the anisotropic damage variables. Estimating the microplastic work from the elastic stresses and strains assuming a Ramberg-Osgood type plasticity law for the microplastic strains and introducing the material parameters A and n as well as the damage warping function ω, the one-dimensional damage evolution equation

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

is obtained. Subsequently, this equation is re-written to a fully three-dimensional form and the model is implemented as a user-defined material model into a commercial finite element program. Full details on the formulation and finite element implementation can be found in an oncoming contribution (Hohe et al. [3]).

3. Example

For validation, the proposed fatigue damage model is applied to an experimental data base on a filament wound carbon epoxy material. Exemplary results for the obtained S-N-curves are presented in Figure 1. In all three cases considered, the numerical prediction is found in a good agreement with the experimental data. Especially the linear shape of the S-N- (Wöhler-) curve in the double logarithmic representation of the fatigue diagrams is recalled in a perfect manner. Despite the distinct scatter of the experimental data, a good quantitative prediction of the fatigue strength is obtained.

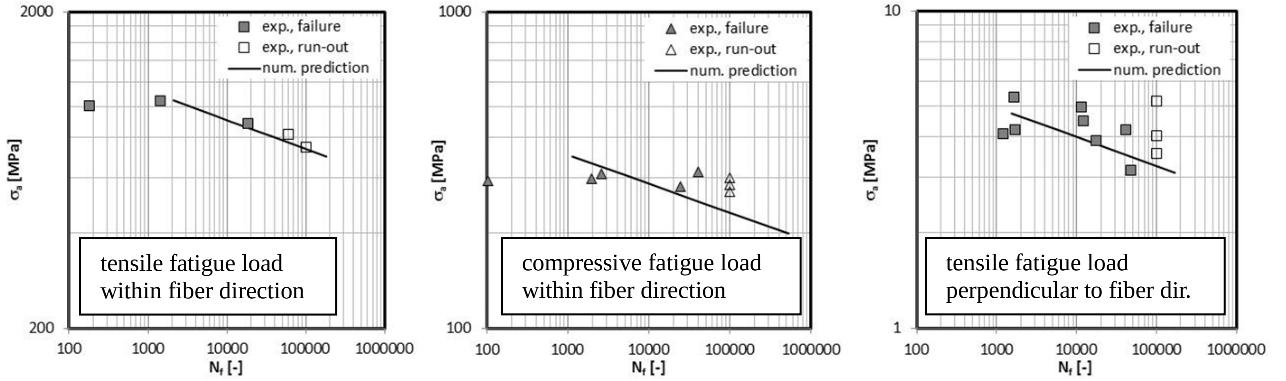

Figure 1: Numerical example.

4. Conclusions

The present contribution is concerned with the definition and implementation of a continuum damage mechanics model for fatigue degradation of CFRP materials. The model is based on a linear elastic base formulation in conjunction with anisotropic damage based on three independent damage variables. The damage evolution is assumed to be controlled by microplastic effects below the overall yield limit of the material. In an application to an experimental data base, the model proves to provide an accurate prediction of the S-N-curves obtained in different testing directions and loading modes.

Acknowledgments The present work has been funded by the German Federal Department of Economic Affairs and Energy (BMWi) under grant no. 03ET6013F. The authors are fully responsible for the contents of this contribution.

References

[1] H. Gauch: *Implementation and validation of a fatigue degradation model for carbon fiber reinforced plastics*, Master Thesis, Karlsruhe Institute of Technology and Fraunhofer IWM, Freiburg 2015, in German.

[2] Hohe, J., Gall, M., Gauch, H., Fliegener, S. and binti Abdul Hamid, Z.M.: A material model for prediction of fatigue damage and degradation of CFRP materials, *Key Eng. Mat.* 742 (2017) 740-744.

[3] J. Hohe, M. Gall, S. Fliegener and Z.M. Abdul Hamid: A continuum damage mechanics model for fatigue degradation of fiber reinforced materials, *submitted*.