14th World Congress in Computational Mechanics (WCCM)
ECCOMAS Congress 2020
Virtual Congress: 11 – 15 January 2021
F. Chinesta, R. Abgrall, O. Allix and M. Kaliske (Eds)

VALIDATION OF AN ENERGY-BASED FATIGUE LIFE MODEL FOR FIBRE REINFORCED PLASTICS UNDER DIFFERENT STRESS RATIOS

K. TITTMANN[1], I. KOCH[1] AND M. GUDE[1]

[1] Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden
Holbeinstraße 3, 01307 Dresden, Germany
karsten.tittmann@tu-dresden.de and http://tu-dresden.de/mw/ilk

Key words: Fibre Reinforced Plastics, Fatigue, Service Strength Analysis, Mean Stress Influence, Model Validation, Computing Methods.

Abstract.

The energy-based fatigue model presented in this work overcomes different shortcomings of existing model approaches, such as the need of separated assumptions for constant life diagrams. By using the range of the normalised strain energy density and a probabilistic based mode interaction approach, a failure mode dependent fatigue model for CFRP is established for directly predicting constant life diagrams and calculating the fatigue life for multiaxial loads with constant amplitude. In this contribution, the ply-based model and some of its main features, such as the consideration of residual stresses or of mode interactions at general three-dimensional stress states, are shortly summarised. The stepwise model validation on different literature datasets is considered in more detail, including prediction of SN-curves with scatter band and constant life diagrams.

1 INTRODUCTION

Due to their excellent material properties, fibre reinforced plastics (FRP) are constantly entering new application areas in the field of mass production, such as automotive industry and consumer goods. To meet the demanding time-to-market requirements of these industries, virtual testing and design are becoming increasingly important and suitable material models are needed. In this context, the service strength analysis is of great relevance in order to guarantee safe usage of FRP structures under cyclic loading conditions. Compared to homogeneous materials FRP show a more complex fatigue behaviour due to their anisotropy and the formation and interaction of numerous damage phenomena especially in the case of realistic multiaxial loads according to Figure 1. A current challenge is the accurate and computationally efficient prediction of the fatigue life for arbitrary multiaxial fatigue loads with different stress ratios.

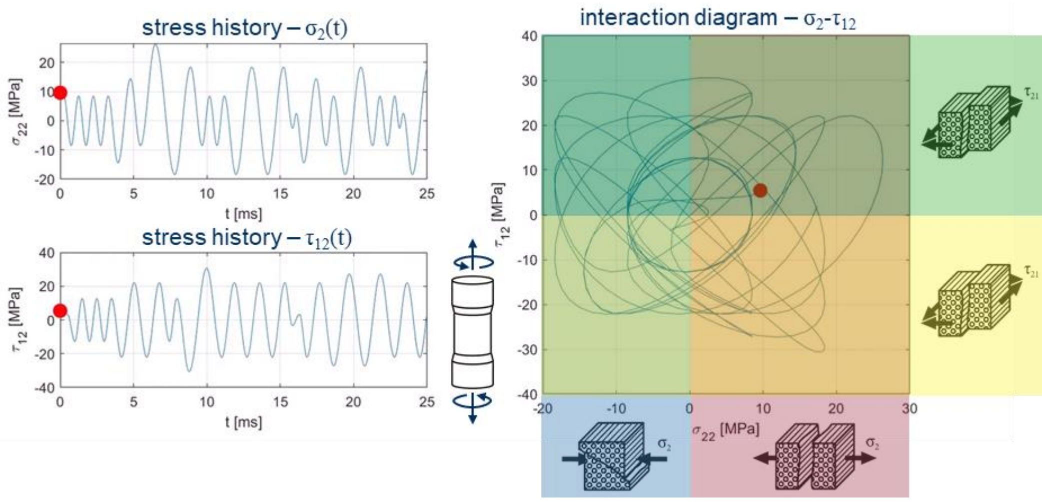

Figure 1: fibre failure modes of composite materials

Extensive efforts have been made previously to develop different models for the lifetime prediction – mostly for constant amplitude loading [1, 2]. However, for arbitrary fatigue loading with variable amplitudes and multiaxial stress states comprising significant out-of-plane stresses, typical for hybrid FRP-metal structures in automotive industry, there are still significant challenges to be tackled. From numerous discussions with structural and application engineers, it has been found that practice oriented fatigue life models for fast and direct application in automotive and related industries should be incorporated in the design and structure validation process with finite element methods. Therefore, models should comprehensively consider three-dimensional states of stresses, multiaxialities and residual stresses. To meet the basic requirements of a reliable design, fatigue models should also consider scatter and provide service strength with regard to probabilities of survival.

2 MODEL CONCEPT AND FEATURES

In the context of this paper a mathematical approach for the prediction of fatigue life under arbitrary fatigue stresses with constant amplitude is called "fatigue model". The energy-based fatigue life model for unidirectional reinforced composites validated in this work accounts for the interaction of different damage phenomena as well as the mean-stress effect [3].

As proposed already in the literature, the range of the elastic strain energy density (SED) – light grey area, Figure 2 – according to

$$\Delta W = |W_{max} - W_{min}| \tag{1}$$

with $W_{max,min}$ being the maximum and minimum SED within a load cycle N, respectively, is considered to be an adequate measure for describing the sensitivity of crack initiation to mean stresses in fibre composite materials [4, 5].

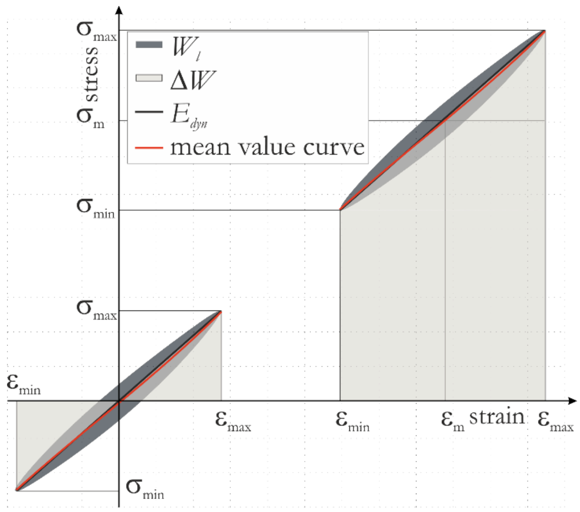

Figure 2: Strain energy density in comparison to other energy measures used in fatigue modelling (storage and loss energy) for two different stress ratios but identical stress amplitudes

By assuming linear elastic, ideally brittle material behaviour and normalising the actual SED to the SED at static failure W_f according to

$$W^c = \frac{W}{W_f} = \frac{{}^1/_2 \cdot \sigma \cdot \varepsilon}{{}^1/_2 \cdot \sigma_f \cdot \varepsilon_f} = \frac{\sigma^2/_E}{\sigma_f{}^2/_E} = F^2 \tag{2}$$

where σ_f and ε_f are the stress and strain at failure, E is the modulus of elasticity, and F is the stress exposure, the load cycle-dependent failure criterion for the presented model can be derived as:

$$\frac{\Delta(F^2)}{\Delta W^c(N)} = 1. \tag{3}$$

Here, Δ denotes the range and $W^c(N)$ is the load cycle-dependent normalised (standardised) critical strain energy density (SSED). The failure criterion is transferred to unidirectional reinforced composite materials with several interacting failure modes by formally assigning it to each failure mode i

$$\Delta W_i^c(N) = \Delta((F^i))^2. \tag{4}$$

Consequently, the equations comprise two fibre failure modes (FF1, FF2) and three inter-fibre failure modes (IFF1, IFF2, IFF3) resulting in the five failure mode-specific exposures $F^{\parallel\sigma}$, $F^{\parallel\tau}$, $F^{\perp\sigma}$, $F^{\parallel\perp}$ and $F^{\perp\tau}$. The mathematical formulation of the modal stress exposures is based on the invariant formulation according to Cuntze [6] and is modified by case distinctions for application to cyclic loads. In analogy to the fracture-mode related failure criterion of Cuntze for static loading, the load cycle-dependent failure criterion for unidirectional reinforced composites is derived from equation (3) by linking the failure-mode specific individual criteria by the interaction coefficient m according to

$$1 = \left(\frac{\Delta((F^{\parallel\sigma})^2)}{\Delta W^c_{\parallel\sigma}(N)}\right)^m + \left(\frac{\Delta((F^{\parallel\tau})^2)}{\Delta W^c_{\parallel\tau}(N)}\right)^m + \left(\frac{\Delta((F^{\perp\sigma})^2)}{\Delta W^c_{\perp\sigma}(N)}\right)^m + \left(\frac{\Delta((F^{\perp\tau})^2)}{\Delta W^c_{\perp\tau}(N)}\right)^m + \left(\frac{\Delta((F^{\parallel\perp})^2)}{\Delta W^c_{\parallel\perp}(N)}\right)^m. \tag{5}$$

The wear-out model according to VDI2014 [7] is used to describe the characteristic load-cycle dependent master-ΔW_i^c- N-curves for each failure mode according to

$$\Delta W_i^c(N) = \left(\frac{1 - V_{g,i}}{N - V_{g,i}}\right)^{N_{g,i}} \tag{6}$$

with the parameters $V_{g,i}$ and $N_{g,i}$. By solving equation (6), the fatigue life for arbitrary combinations of amplitudes and mean stresses can be determined for multiaxial cyclic loading situations triggering multiple interacting failure modes. Inputs for the calculation process are stress tensors for maximum and minimum load comprising all stress components ($\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{13}, \tau_{12}$), typically gained from finite element simulation.

The presented approach features the direct calculation of constant life diagrams without the need for additional mean stress modelling such as multi-linear, anisomorphic or bell shaped approaches known from literature. Moreover, it is possible to consider multiaxial proportional loadings and residual stresses as shown in Figure 3. It is noted ones again that the given constant life curves in Figure 3 are the direct result of solving equation 5 for different stress states without further modelling input.

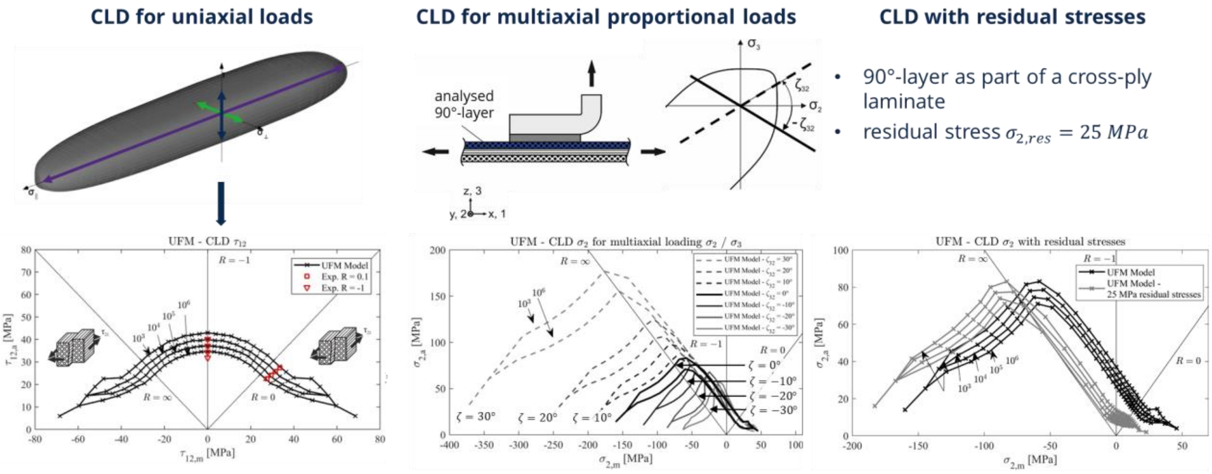

Figure 3: Visualisation of the model features: Prediction of constant life diagrams from basic fatigue data (left), evaluation of the effect of proportional multiaxial loadings (middle) and residual stresses (right)

The model has further developed for considering the scatter of the quasi-static and fatigue strength input data. Two different approaches (PFP and 50%), handling the scatter of static strength for calculating the SED differently, have been developed. The methods of considering the interacting distributed values of static and fatigue strength are not discussed in detail here. But for the available experimental data, both approaches were found to be largely equivalent, as highlighted in Figure 4.

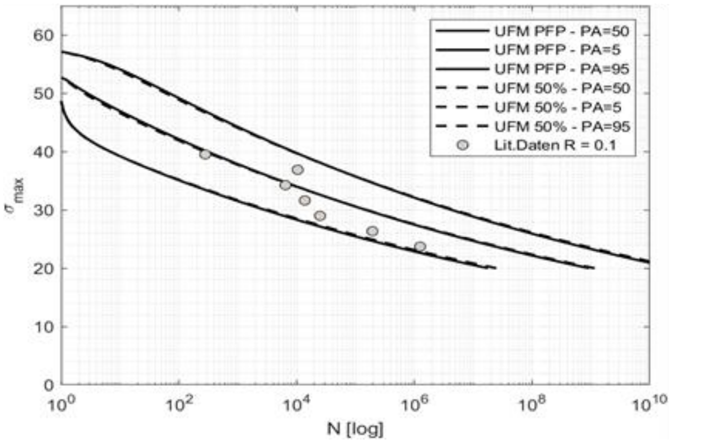

Figure 4: Comparison of methods for considering scatter of static and cyclic strength within the presented framework, experimental data from [8]

3 VALIDATION ON LITERATURE DATA

For validating the proposed fatigue model, a stepwise validation approach with growing complexity according to Figure 5 is established. The two first validation steps consider the prediction of fatigue failure regarding pulsating loads only. Fatigue data from unidirectional material with pulsating load in the material axes is required for validation level 1. At validation level 2 off-axis or multiaxial laminates are considered that exhibit intrinsic multiaxiality and mode interaction. Validation levels 3 and 4 are characterised by alternating loads that trigger multiple opposing failure modes in each single cycle. At level 3 again fatigue data from unidirectional material but with alternating load in the material axes is considered (e.g. tension-compression fatigue loading on unidirectional plies in the material axes). At validation level 4 fatigue data from multiaxial laminates and off-axis plies under alternating loads are used. At this highest validation level a maximum of failure mode mixture during cycling and mean stress effects have to be predicted accurately.

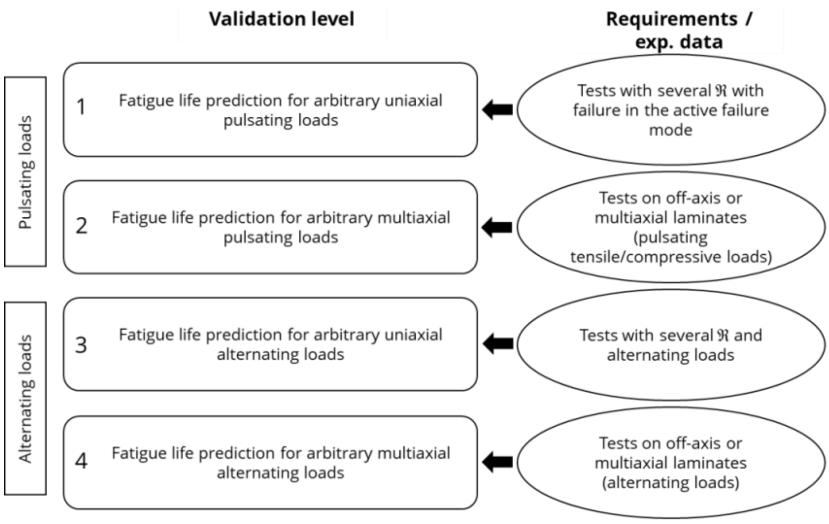

Figure 5: Fatigue model validation levels

Common to all validation levels is the need for sufficient quasi-static and fatigue data for model calibration. For each individual material, data from uniaxial pulsating loading in the material axis is required.

3.1 Materials and model calibration

A literature survey revealed several suitable data sets from which two are selected to be presented here.

The first data set has been published by Jen et al. [9] and contains quasi-static as well as fatigue data for AS4 carbon fibre-reinforced PEEK, manufactured by the Imperical Chemical Industries (ICI) Fiberite Company. Unidirectional, cross-ply as well as quasi-isotropic laminates were manufactured at 400°C for about 15 min from which strip specimens according to ASTMD3039-76 for tensile loading and half of the specimen length for compression loading were taken by diamond blade cutting.

The second data set has been published by El Kadi et al. [4] and contains data for the glass fibre reinforced prepreg material Scotchply Reinforced Plastic type 1003 under pulsating tensile loads. This composite is a nonwoven, glass fibre-reinforced epoxy resin material. The glass fibre used is a continuous E-type filament. The material is pressed in a closed mould at 150 °C over 12 h. For material characterisation under tensile load, strip samples according to ASTM D3039 were again used. For compression a shorter free length and, in case of 0°-specimens, an anti-buckling device is applied. To enable validation at levels 3 and 4 for alternating loads, the data from El Kadi et al. is additionally supplemented with the test results of Sun et al. [10], who also investigated a uniaxial glass fibre-reinforced epoxy resin material.

According to the model description in section 2 the published data of pulsating cyclic loading on unidirectional plies in the material axis (single failure modes) are transformed and approximated by the wear-out approach (6) gaining the master-ΔW_i^c- N-curves for each failure mode. The resulting master curves, as main input for the fatigue model, are shown for the CF-PEEK material in Figure 6 (right) and for the GF-EP material in Figure 7. It is concluded that the wear-out approach is suitable to describe the SSED for different failure modes and over a wide range of cycle numbers for two very different materials.

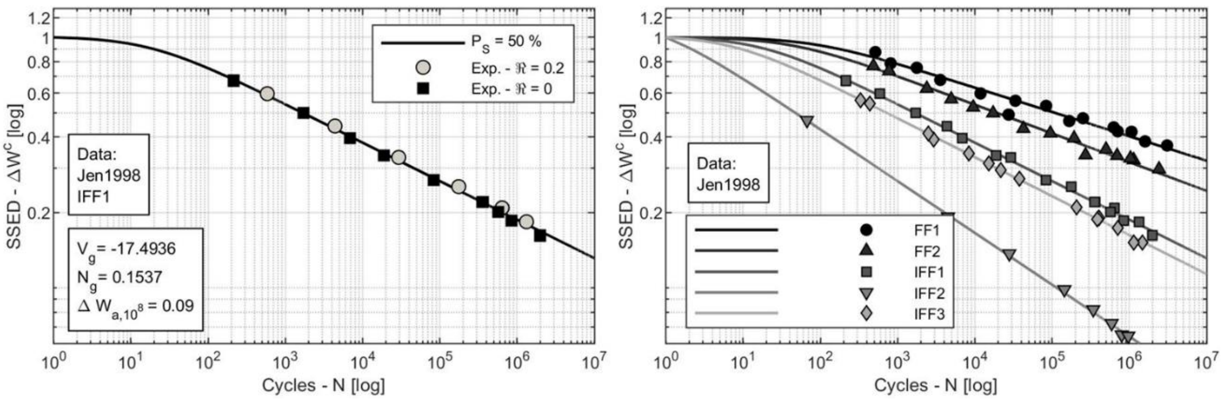

Figure 6: Identification of fatigue model parameters for CF-PEEK from [9]

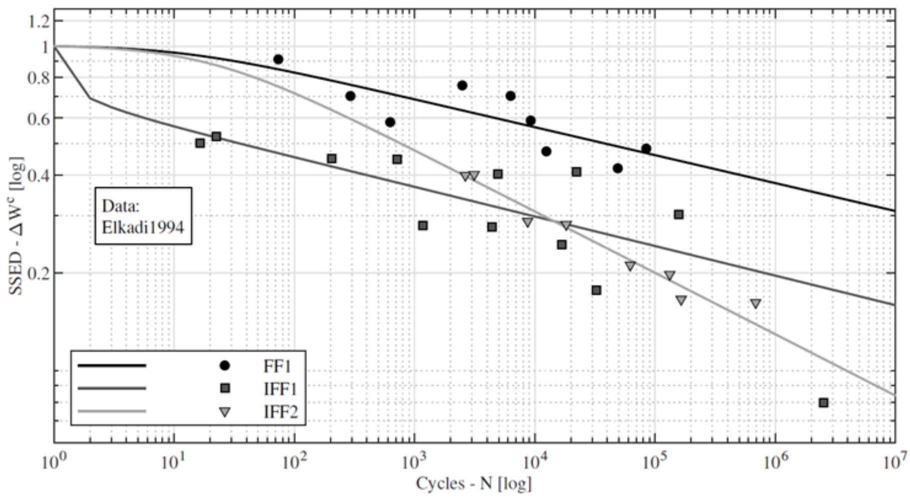

Figure 7: Identification of fatigue model parameters for GF-EP from [4]

3.2 Model validation

For validation, the individual material specific calibrated model setups are used to predict SN-curves for specific stress ratios and fibre orientations on the one hand and complete constant life diagrams on the other, which are compared with the experimental data.

The model validation regarding level 1 is given in Figure 6 (left) for the CF-PEEK material. It is exemplary shown that fatigue data of different stress ratios but of the same failure mode (IFF1) collapse very well with the given model equations into the master-ΔW_i^c-N-curves . By comparing the experimental results with the calculated constant life curves in Figure 8, comparably good results are also found for the other failure mode (IFF3) in the $\pm\sigma_2$-stress domain. The results of validation level 1 confirm that the master-curve approach based on the range of normalised strain energies is valid for individual failure modes.

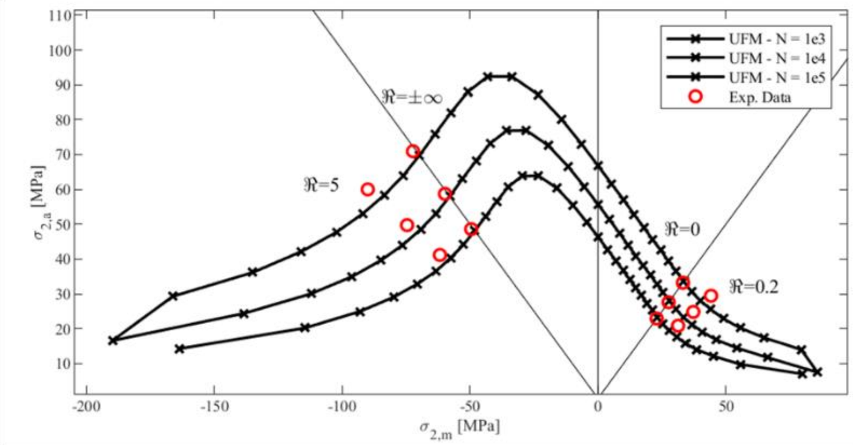

Figure 8: Modelled CLD in comparison to experimental data used for model calibration [9]

The second validation level addresses fatigue at proportional in-phase multiaxial stresses triggering more than one failure mode. Experimentally, this is achieved by pulsating fatigue loading of single-layer off-axis strip specimens. Exemplary results for both materials compared to the modelling results are plotted in Figure 9. The left side shows the results for CF-PEEK and the right hand side for GF-EP. The data from Jen et al. (CF-PEEK) included fatigue tests at $R = 0.2$ using specimens with 45° (Figure 9 top left) and 60° (Figure 9 bottom left) fibre angles. The resulting SN-curves are characterised by low scatter and slope. The model predicts this behaviour accurately.

In difference to CF-PEEK, the experimental results for GF-EP at 45° fibre angle and a stress ratio of $R = 0.5$ are characterised by a large scatter band, which is again accurately predicted by the model (Figure 9 top right). The good modelling results are also confirmed when predicting the fatigue life of GF-EP at 71° and 19° fibre angle (Figure 9 bottom right).

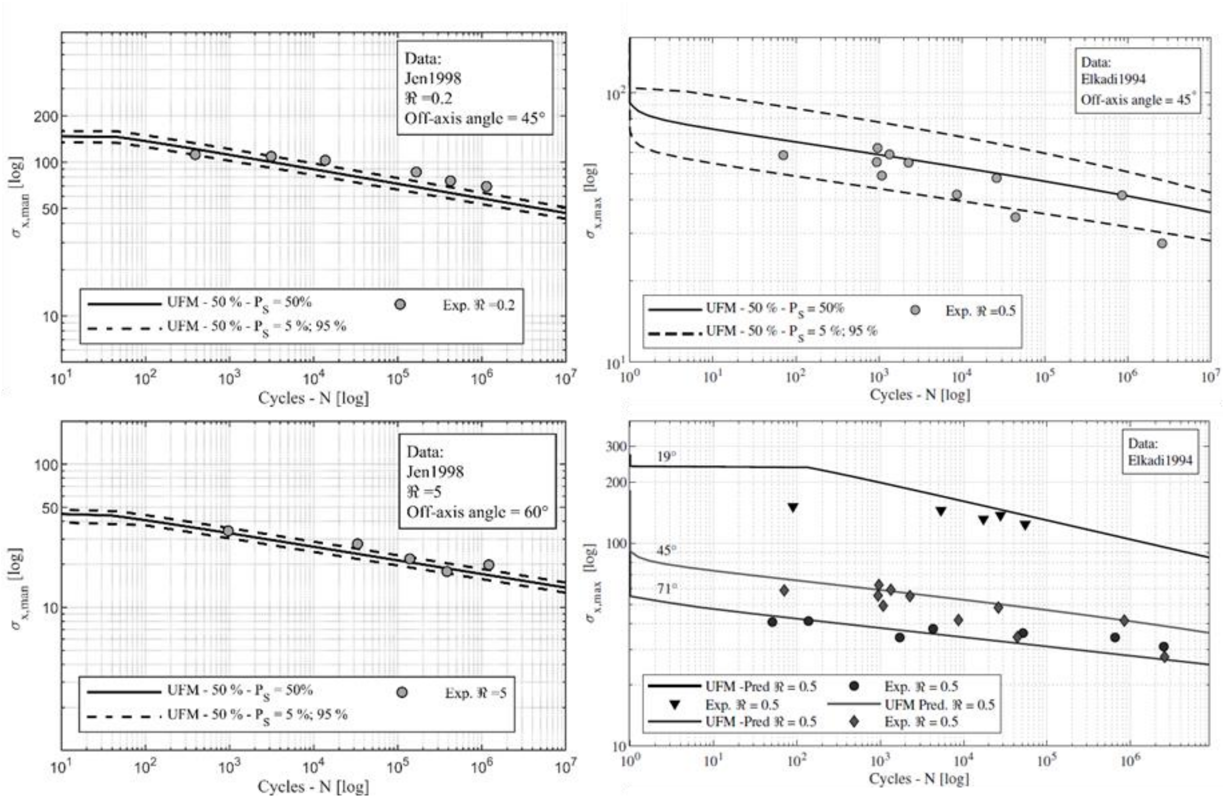

Figure 9: Model validation at level 2, pulsating fatigue stresses with intrinsic multiaxiality triggering more than one failure mode

The results for the highest validation levels 3 and 4 are given in Figure 10. In Figure 10 on the left, the predicted SN-curve for a stress ratio of $R = -1$ for single-layer GF-EP specimen loaded transversely to the fibre direction is compared with experimental results. Here, two opposite failure modes, inter fibre failure due to tension (IFF1) and inter fibre failure due to compression (IFF3), are activated during each single cycle. The probabilistic combination of the different failure modes in the presented fatigue model according to equation (5) and the developed method for considering scatter accurately predict not only the slope and position of the SN-curve, but also the scatter band.

Using the data of El Kadi et al. combined with Sun et al. for GF-EP, the highest validation level 4 is possible. Here, proportional multiaxial stresses are combined with alternating loads triggering different failure modes. Again, the model is able to predict the behaviour accurately for a wide range of fibre angles. Significant differences between prediction and experimental results are only found for the fatigue data of GF-EP at 19° fibre angle and $R = -1$. Here the fatigue life is overestimated. Possible reasons for that may be found in the high ratio of shear deformations and related accumulation of irreversible strain, when considering the strictly linear nature of the model approach.

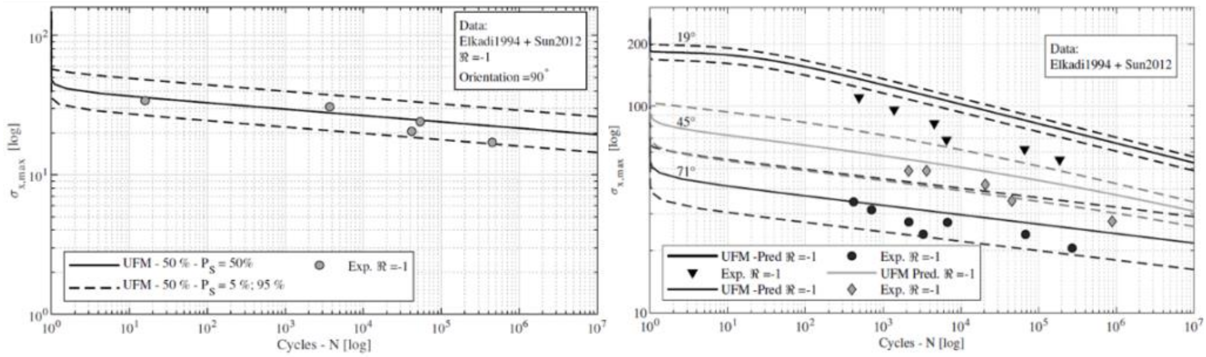

Figure 10: Model validation on level 3 (left) and 4 (right)

4 SUMMARY

The fatigue of fibre-reinforced composites requires interdisciplinary research and a strong interaction of material science, applied mechanics and numerical simulation. In order to provide a practice-oriented fatigue life prediction for continuous fibre-reinforced composites under consideration of material specific failure modes and a strong orientation towards finite element methods, a strain energy based approach has been developed. This layer-based fatigue model enables fatigue life prediction of fibre composites considering intrinsic and extrinsic multiaxiality and arbitrary mean stresses. An essential part of the modelling strategy is the consideration of scatter to provide fatigue life taking into account probabilities of survival. Its validation is exemplary shown here for single- and multi-layered CF-PEEK and GF-EP from literature. By comparing the predicted SN-curves at 50%, 5% and 95 % survival probability for different stress ratios and proportional multi-axial stresses with experimental data, the new formulation is found to be valid. Predicted constant life diagrams without further assumptions highlight the versatility of the approach.

REFERENCES

[1] Vassilopoulos, A. P. and Keller, T. *Fatigue of fiber-reinforced composites*. Springer Science & Business Media, (2011).

[2] Koch, I., Zscheyge, M., Tittmann, K. and Gude, M. Numerical fatigue analysis of CFRP components. *Composite Structures (2017)* **168**:392-401.

[3] Tittmann, K., Wacker, J., Koch, I., Gude, M. and Melz, T. Testing and modelling strategy for application-oriented service strength analysis of composite materials in hybrid

adhesive joints. *Proceeding of the 18th European Conference on Composite Materials*, Athens, Greece (2018).

[4] El Kadi, H. and Ellyin, F. Effect of stress ratio on the fatigue of unidirectional glass fibre/epoxy composite laminae. *Composites* (1994) **25**: 917-924.

[5] Shokrieh, M.M. and Taheri-Behrooz, F. A Unified Fatigue Life Model Based on Energy Method. *Composite Structures* (2006) **75**: 444-450.

[6] Cuntze, R.G. Efficient 3D and 2D Failure Conditions for UD Laminae and Their Application within the Verification of the Laminate Design. *Composites Science and Technology* (2006) **66**:1081-1096.

[7] VDI Verein Deutscher Ingenieure e.V. *Entwicklung von Bauteilen aus Faser-Kunststoff-Verbund – Berechnungen - VDI 2014* Blatt 3. VDI-Gesellschaft Materials Engineering (2006).

[8] Hahne, C. *Zur Festigkeitsbewertung von Strukturbauteilen aus Kohlenstofffaser-Kunststoff-Verbunden unter PKW-Betriebslasten*. PhD thesis, TU Darmstadt, Germany (2014).

[9] Jen, M. H.R. and Lee, C. H. Strength and life in thermoplastic composite laminates under static and fatigue loads. Part I: Experimental. *International Journal of Fatigue* (1998) **20**:605–615.

[10] Sun, X.S., Haris, A., Tan, V.B.C., Tay, T.E., Narasimalu, S. and Della, C.N. A multi-axial fatigue model for fiber-reinforced composite laminates based on Puck's criterion. *Journal of Composite Materials* (2012) **46**:449–469.