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SHORT-TIME APPROACH FOR FATIGUE LIFE ESTIMATION OF MULTIFUNCTIONAL COMPOSITES

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ABSTRACT

Multi material design is one promising approach to fulfil the ambitious demands for future aircraft and vehicles. Combining the advantages of metal- and fiber reinforced polymer-structures is a novel concept to create multifunctional materials. Because primary structural applications are subjected to cyclic loadings, fatigue properties are of central interest. Therefore, the present study introduces a time and resource-saving concept to analyze the fatigue strength of multifunctional composites by less experimental effort. The main focus of this paper is on a new short-time procedure for fatigue life estimation of polymer composites based on constant amplitude as well as cyclic load increase tests. The procedure for fatigue life assessment shows a reliable correlation between experimental data of constant amplitude tests and calculated S-N curves for both investigated laminates in the low and high cycle fatigue regime.

1 INTRODUCTION

The requirements for next generation aircraft with reduced emissions and lower fuel consumption are highly ambitious. In particular, reduction of mass in the primary structure is a necessary goal. The emerging role of carbon fiber reinforced polymers (CFRP) is shown by its share of over 50 % in total weight in the latest generation of civil aircrafts like Airbus´ A350 and Boeing´s 787 [1,2]. Nevertheless, the significant weight saving potential by the usage of carbon composites is limited because of lower electrical functionality as well as brittle failure behavior compared to metallic concepts based on lightweight alloys [2]. A promising approach to create multifunctional lightweight structures is the intrinsic hybridization of steel and carbon fibers in one composite (MCFRP). A gradual failure behavior was already successfully achieved by Fotouhi et al. and Czél et al. [3, 4] by combining glass and carbon fibers to a hybrid composite laminate. Former research concentrated on modifying the matrix systems to enhance the needed electrical properties but without significant breakthroughs [5-8]. The idea to combine the single advantages of metallic and composite concepts is already realized in the form of fiber metal laminates (FML) like GLARE® or ARALL® which are already successfully used for specific aircraft components [9, 10]. An outstanding combination of high stiffness and high strain-to-failure was reached by Callens et al. [11, 12] by integrating thin stainless steel fibers in polymer composite laminates. The combined advantages in relation to ductile failure behavior and enhanced electrical conductivity of thin steel fibers as well as the excellent tensile strength of carbon fibers, is a promising step forward to a new level of multifunctional composites. The developed metal-fiber and carbon-fiber-reinforced-polymers (MCFRP), which are introduced later, have shown significant improvements in electrical conductivity, monotonic tensile behavior as well as energy absorption [13]. Structural applications in aircraft are also subjected to cyclic loadings. In order to reduce the effort of maintenance, the design rule of “no-crack-growth” for the entire time in service [2] is state-of-the-art for the current application of CFRP in primary load-carrying aircraft structures. Therefore the fatigue properties of CFRP as well as failure mechanisms are highly relevant. Stinchcomb et al. [14], Reifsneider [15] and Talreja et al. [16] investigated the fatigue properties of conventional CFRP intensively. Some attempts to enhance fatigue properties of CFRP laminates were shown e.g. by Knoll et al. [17] and Fenner et al. [18] by modifying the matrix system with carbon nanotubes (CNT). The fatigue properties of hybrid composites with embedded steel fibers (MCFRP) were currently investigated in [19]. A robust fatigue life prediction of polymer or even hybrid composites is a mandatory step to reduce the effort of experimental fatigue characterization and component development. While [20, 21] concentrate on approaches for fatigue life prediction based on stiffness degradation models, Brunbauer et al. introduced a software-based prediction of the fatigue life using FEMFAT Laminate software [22]. The usage of strain measurements [23] and change of electrical resistance [24] were further attempts to create a reliable experimental database to predict the fatigue life of composites. In the present study a time and resource-saving concept to analyze the fatigue behavior of composites is developed and introduced. The database used for the novel concept is mostly generated by one single load increase test per investigated laminate. Every experiment is monitored by high precision temperature and strain measurements as well as determination of changes in stiffness and resistivity. A related concept for metallic materials (PhyBaL®) was already successfully applied at TU Kaiserslautern [25]. S-N curves in the HCF-regime can be described in principle by Basquin´s law, equation (1)

$$\sigma_a = \sigma_f^{\prime} * (2N_f)^b \qquad \text{Eq. (1)}$$

Based on findings by Morrow [26] the fatigue strength exponent for monolithic metallic materials is described by the following equation (2).

$$b = \frac{-n^{\prime}}{1+5n^{\prime}} \qquad \text{Eq. (2)}$$

While equation (1) describes the relation between applied stress amplitude σ_a and number of cycles to failure N_f, equation (2) is based on an empiric relation [26] between applied stress amplitude and the total plastic strain energy to fracture, describing the correlation between the fatigue strength exponent b and the cyclic hardening exponent n`. In a double logarithmic plot the slope for most metallic materials is around -0.25. A detailed explanation of this empiric relation is given and validated in [26]. However, the evaluated slope of -0.25 is not valid for composite materials. For metallic materials the fatigue phenomenon is based on plastic deformation leading to a negative slope of the S-N curve. For polymer composites this negative slope is caused by a damage accumulation and the fatigue phenomenon is based on matrix cracks, interface decohesion and delamination of single plies. So we propose to rename the exponent n´ to cyclic damage exponent d´. In chapter 4 a detailed explanation is given for the adapted equation for the fatigue strength exponent and the application for polymer composite laminates.

2 MATERIAL AND SPECIMEN DESIGN

For introducing our novel method for fatigue life prediction a conventional CFRP laminate, which serves as reference, and the newly developed MCFRP laminate are analyzed and compared. A multiaxial 13-layered CFRP laminate with a typical stacking sequence for fuselage applications serves as reference while the MCFRP combines a core of 13 pure CFRP layers with the same stacking sequence and additional 4 plies of metastable austenitic steel fibers with a diameter of 60 µm, see Figure 1.

The chosen laminates were manufactured by a combination of tape deposition and filament winding at the Institute for Composite Materials (IVW, Kaiserslautern, Germany). Compared to a homogenous distribution of steel fibers a so-called layer-separated approach provides mechanical advantages [13]. Moreover, the concentration of steel fibers at the surface provides an improved integrity in case of lightning strikes. The mechanical properties were determined in tensile tests according to DIN EN ISO 527-4. Selected mechanical and physical properties of both composites are summarized in Table 1.

The presented composite laminates are cured using autoclave technology at a pressure of 6.5 bar with a 1-hour dwell time at a process temperature of 135 °C, followed by a 3-hour dwell time at T = 180 °C with a temperature rate of 2 °C/min. The matrix system is an epoxy-based resin, commercially available from Cytec (Cycom 977-2), reinforced with HTS40 carbon fibers supplied by Toho Tenax. All laminates were manufactured at IVW (Kaiserslautern, Germany) as part of a joint research project funded by the German Research Foundation.

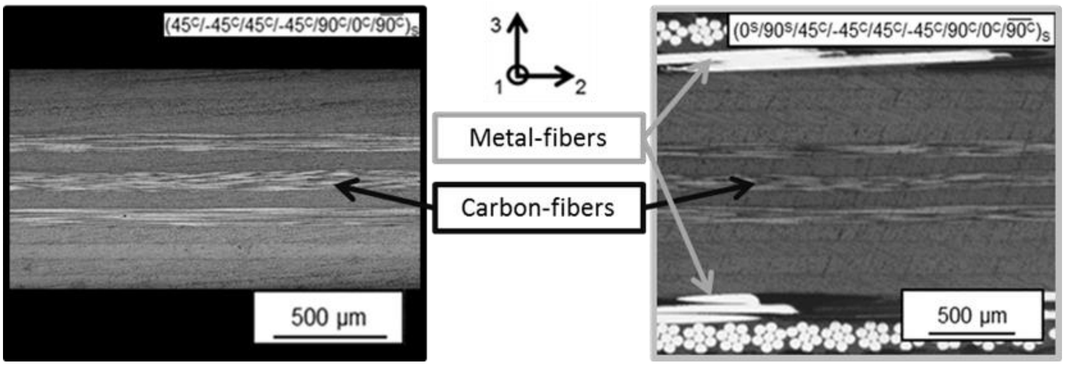


Figure 1: Light optical micrographs of CFRP (left) and MCFRP (right) multidirectional laminate layups

Laminate	CFRP	MCFRP
Thickness (mm)	1.6	2.14
Mass-density (g/cm³)	1.59	2.82
Carbon fiber (Vol. %)	61.6	46
Metal fiber (Vol. %)	0	19.5
UTS in 1-dir. (MPa)	497±22	482±14
Young´s Modulus in 1-dir. (GPa)	40.3±0.5	33.2±0.8

Table 1: Selected properties of multidirectional laminates

3 EXPERIMENTAL SETUP

Stress-controlled load increase tests (LIT) and constant amplitude tests (CAT) were performed with a frequency of 5 Hz, sinusoidal waveform and a stress ratio of R = 0.1. The experimental setup is given in Figure 2. The fatigue experiments with constant stress amplitudes were performed to validate the calculated S-N curves while the load increase tests provided the database for the calculation concept.

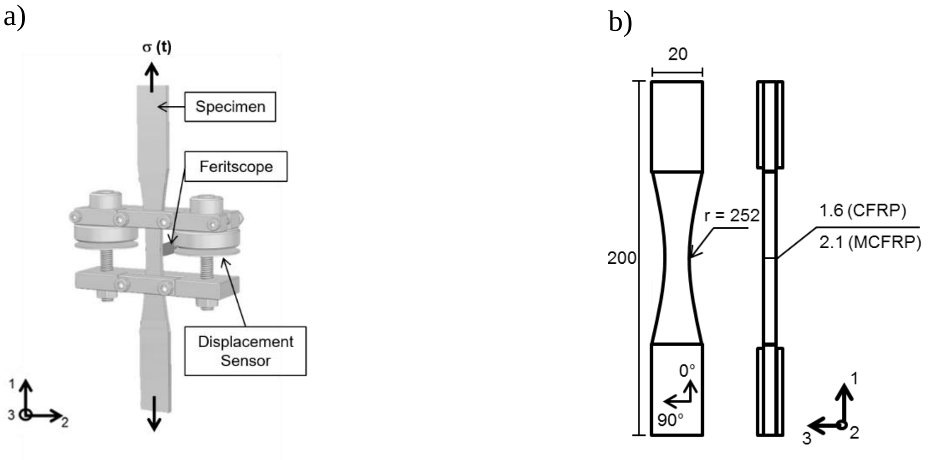


Figure 2: a) Schematic representation of the experimental setup b) specimen geometry (dimensions in mm)

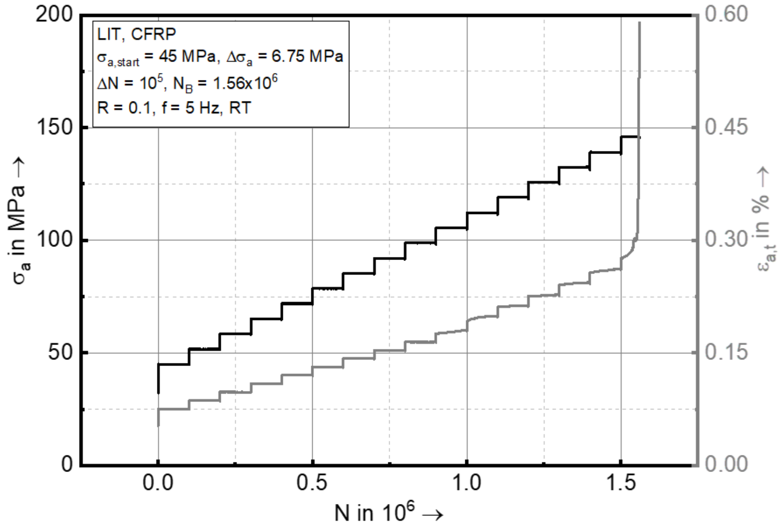
A capacitive displacement sensor with a gauge length of 30 mm captured the total strain amplitude. Based on the measured gradient of each cycle's stress-strain hysteresis the stiffness degradation was determined by a comparison to the initial stiffness of each MCFRP specimen.

In case of the MCFRP laminate, a magnetic inductive measuring device (Feritscope® FMP30, Helmut Fischer GmbH, Sindelfingen - Germany) was applied to monitor the changes of magnetic phase fraction $\Delta\xi$ in the metastable steel fiber layers near the surface. The measuring principle is described in [27]. The geometry with a constant radius of 252 mm (see Figure 2 b) was chosen, especially for magnetic measurements to ensure highest stress amplitudes at a predefined location with a cross sectional area of 21.4 mm². To ensure a smooth force transmission without inducing damage the ends of the specimens were bonded with GFRP tabs.

4 RESULTS AND DISCUSSION

The database for the new short-time concept to estimate the fatigue life of the introduced laminates was generated by single load increase tests of CFRP see Fig.3 a) and MCFRP b). The fatigue induced damage for CFRP and MCFRP up to $2\text{x}10^6$ cycles as well as the fatigue strength itself were investigated in detail and discussed in [19]. In addition to standard measurement techniques the magnetic volume fraction $\Delta\xi$ and the stiffness degradation $E/E_{1,0}$ were captured for the MCFRP laminate, visible in Fig. 3 b). A clear correlation between rising magnetic volume fractions $\Delta\xi$ in the steel fiber layers and decrease of stiffness is given. Further results and measurement techniques are introduced in [19]. An identical step width of $1\text{x}10^5$ cycles was chosen for both laminates. The stepwise increase as well as the initial stress level was equal for both composites. For the determination of the cyclic damage exponent d` the values of the control variable are plotted in a double logarithmic scale over a specific value representing the materials response to cyclic loading. In our case, according to the results of LITs, the stress amplitude σ_a (black), and the elastic strain amplitude $\varepsilon_{a,t}$ (grey) were captured at half of the step width. In Fig. 3 a) and b) exemplary results of two selected LITs in the High Cycle Fatigue regime (HCF) are shown. The results for the calculation of the fatigue damage exponent d´, based on LITs in the Low Cycle Fatigue regime (LCF) (f = 0.2Hz), are shown in Fig. 3 c). A significant influence of the frequency on the fatigue behavior of both laminates was not observed, visible in the lower graph of Fig. 4. The CFRP laminate shows different gradients and therefore different cyclic damage exponents n` for the LCF and HCF regime, while the MCFRP laminate shows an unchanged behavior. The correlation of fatigue strength exponent b and cyclic damage exponent n´ developed by Morrow is given in equation 2. It is based on an empirical correlation (4) between the cumulative irreversible deformation energy of several constant amplitude tests and the corresponding stress amplitude which was applied.

a)



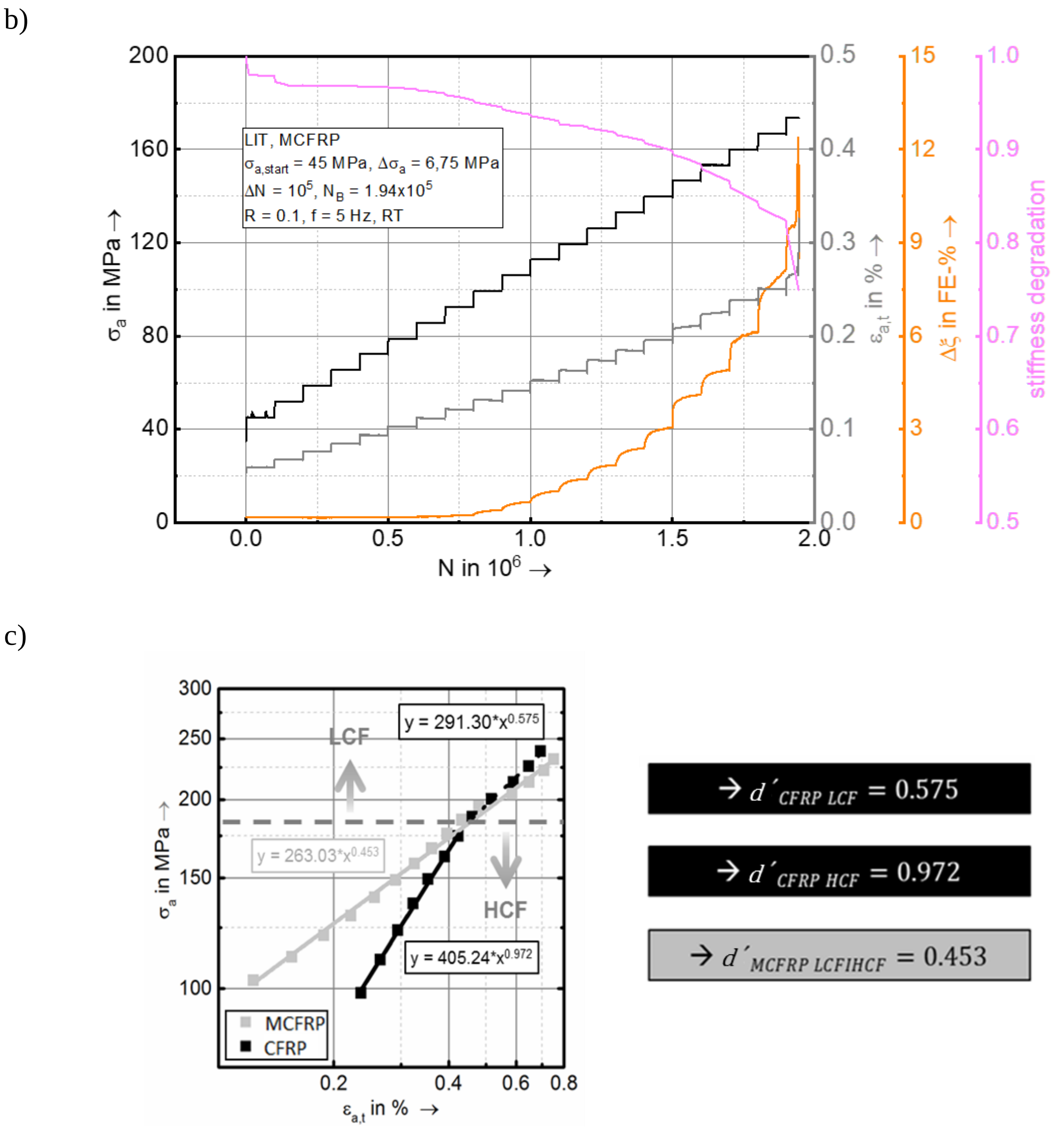


Figure 3: a) LIT of a CFRP laminate b) LIT of a MCFRP laminate c) Morrow´s law based on stress-controlled Load Increase Tests for CFRP and MCFRP laminates acc. [28]

The validity of (5) is also proven for metallic materials within [26]. A combination of Basquin´s law (1) and the following equations (4) and (5) gives equation (2) by mathematical transformations acc. [26, 28].

$$\sigma_a \sim (\Delta W * N_f)^{-\frac{1}{4}} \qquad \text{Eq. (4)}$$

$$\Delta W \sim \sigma_a^{\frac{1+d'}{d}} \qquad \text{Eq. (5)}$$

At first the fundamental correlation between irreversible deformation energy and corresponding applied stress amplitude had to be evaluated to modify the fatigue strength exponent for composite materials. In several analyzed constant amplitude fatigue experiments the cumulative plastic strain amplitude was determined until specimen failure. By considering a stress strain hysteresis we could assume that the plastic strain amplitude multiplied by the corresponding stress amplitude σ_a is almost proportional to the irreversible deformation energy in case of constant stress amplitudes.

A further assumption which was made is the validity of equation (5) not only for monolithic metallic materials but also for composites. In the upper part of Fig. 4 the applied stress amplitude was plotted over the cumulated plastic strain amplitudes $\sum_{n=1}^{N_f} \varepsilon_{a,p,n}$ multiplied by the corresponding stress amplitude σ_a of selected constant amplitude tests. Due to different cyclic damage exponents of the CFRP laminate in the LCF and HCF regime the analysis was divided. The given equations in Fig. 4 provide the needed exponents, which led to a laminate-specific correlation between applied stress amplitude and irreversible strain energy.

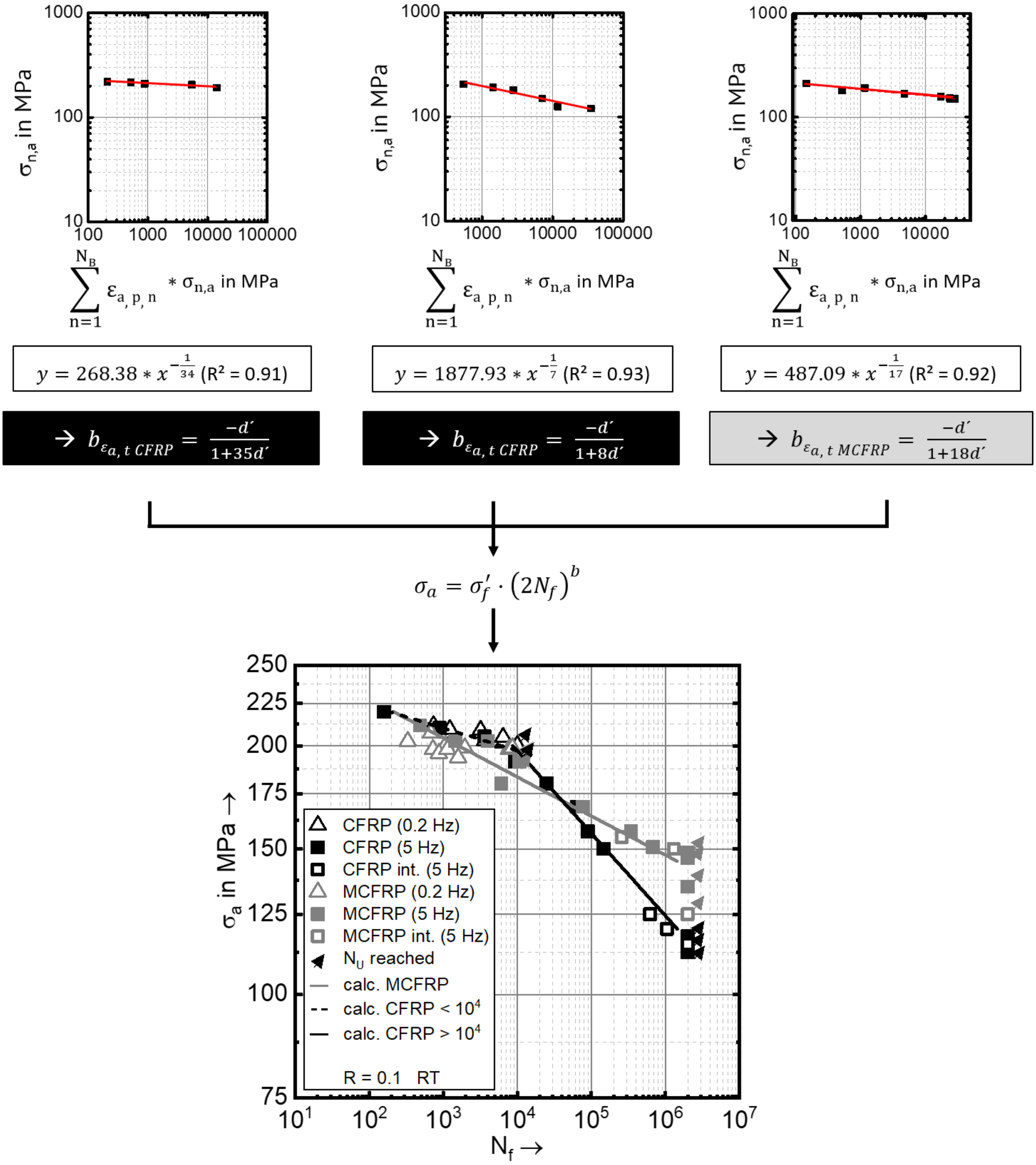


Figure 4: Evaluation of the correlation between applied stress amplitude and the cumulative plastic strain amplitude (upper graphs) and calculated S-N curves for CFRP and MCFRP laminates (lower graph)

Based on the assumption of equation (6) being valid and the following mathematical transformation and equations (7) and (8), the calculation of the fatigue strength exponent b is exemplary introduced for the CFRP laminate in the LCF regime:

$$\sum_{n=1}^{N_f} \varepsilon_{a,p,n} \sim \Delta W * N_f \qquad \text{Eq. (6)}$$

$$\sigma_{n,a} = (\Delta W * N_f)^{-\frac{1}{34}} \qquad \text{Eq. (7)}$$

$$\sigma_a = \sigma_a^{\frac{-(1+d')}{34d'}} * N_f^{-\frac{1}{34}} \qquad \text{Eq. (8)}$$

$$\Leftrightarrow \ \sigma_a^{\frac{(1+35d')}{34d'}} = N_f^{-\frac{1}{34}}$$

$$\Leftrightarrow \ \sigma_a^{\frac{-(1+35d')}{d'}} = N_f$$

$$\Leftrightarrow \ b_{CFRP,LCF} = \frac{-d'}{1+35d'}$$

Identical mathematical transformations led to the different fatigue strength exponents for the conventional CFRP laminate in the HCF regime and the MCFRP laminate, illustrated in Figure 4. The gradients of the S-N curves can be determined using Basquin´s law (1) and the substitution of the fatigue strength exponents for the different materials. Due to the anticipated slightest scatter, the S-N curves are based on the constant amplitude test of highest stress amplitude in the related fatigue regime. The diagram shown in the lower part of Fig.4 illustrates the good correlation of the calculated S-N curves and the experimental data. The different gradients of the S-N curves in the LCF and HCF regime for the CFRP laminate can also be mapped by the introduced short-time procedure for fatigue calculation. Further details will be given during the talk at ICCM22.

5 CONCLUSION AND SUMMARY

A time and resource-saving concept for fatigue life estimation of polymer composites is introduced and validated by experimental data. Load Increase Tests (LIT) are carried out with a frequency of 5 Hz and a stress ratio of $R = 0.1$ providing the needed database for the calculation concept. The stress amplitude σ_a is plotted over the elastic strain amplitude $\varepsilon a,t$, based on the different material responses at half of the step width for each single step of the LIT. The novel method for fatigue life calculation of composites is based on a successfully applied short-time procedure for monolithic metallic materials [25]. By analyzing the cumulated plastic strain amplitude of selected constant amplitude tests, the fatigue strength exponent b is recalculated for both laminates. The S-N curves for CFRP and MCFRP in the LCF and HCF regime are calculated by using Basquin´s law and in consideration of the recalculated fatigue strength exponents. Comparing the computed S-N curves with an already existing experimental database, a strong correlation is presented. Furthermore different slopes of S-N curves in the LCF and HCF regime can be calculated by the introduced procedure. For further applications the validity of the calculated fatigue strength exponents should be checked for different fiber and matrix systems as well as laminate setups.

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