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A novel short-time concept for fatigue life estimation of carbon (CFRP) and metal/carbon fiber reinforced polymer (MCFRP)

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ABSTRACT

For structural applications in the automotive and aircraft industries carbon fiber reinforced polymers (CFRP) have become increasingly important because of their outstanding strength-to-density ratio. A brittle failure behavior, poor damage tolerance and an insufficient level of electrical conductivity are drawbacks compared to monolithic metallic concepts which lead to a limited lightweight potential of composites. The integration of thin metal fibers as well as carbon fibers (MCFRP) is a promising new approach to advance the mechanical properties of conventional CFRP-structures. Structural components are subjected to cyclic loads during their lifetime. The fatigue behavior itself of both laminates – MCFRP and CFRP - was intensively investigated in Backe et al. [1]. The aim and novelty of the present study is a time- and resource-saving concept to analyze the fatigue behavior of composites. Therefore, the focus is on a new short-time procedure for fatigue life calculation of composites based on several cyclic load increase tests of each laminate. A clear correlation between experimental data of various constant amplitude tests with varied frequencies and calculated S-N curves is shown for MCFRP and CFRP laminates.

1. Introduction and fundamental idea

Structural mass reduction by smart material solutions is a necessary goal to fulfil the ambitious demands of next generation automotive and aircraft concepts. Especially in the case of primary structural applications in modern aircrafts like the Airbus A350 and Boeing 787 a share of over 50 wt% composite materials in total shows the emerging role of carbon-fiber-reinforced-polymers (CFRP) [2,3]. The substitution of metallic concepts based on lightweight alloys by CFRP offers a significant weight saving [3]. Notwithstanding, the insufficient level of electrical conductivity as well as the brittle failure behavior are leading to design rules limiting the lightweight potential of CFRP structures. The hybridization of conventional CFRP laminates is an approach to create multifunctional and damage tolerant lightweight structures. Fotouhi et al. and Czél et al. [4,5] successfully achieved a gradual failure behavior by combining glass- and carbon-fibers to a hybrid composite laminate. Dealing with the challenge of enhancing the electrical conductivity, researches [6–9] have tried to concentrate on modifying the matrix system but a significant breakthrough in solving these electrical issues has not yet been achieved. The basic idea of fiber-metal laminates (FML) [10] such as GLARE® and ARALL®, is the combination of advantages of metal and fiber-reinforced polymers. FML are quite well studied and successfully applied through the integration of metallic sheets or foils [11,12]. The integration of thin stainless steel fibers in a polymer composite leads to an excellent combination of high stiffness and high strain-to-failure proven by Callens et al. [13,14]. The combination of advantages in electrical functionality and ductile failure behavior of distributed thin steel fibers, as well as the outstanding tensile strength of carbon fibers, is a promising approach to create a new level of multifunctional composites. The newly developed metal-fiber and carbon-fiber-reinforced-polymers (MCFRP) has shown significant improvements in monotonic tensile and energy absorption behavior as well as electrical conductivity [15]. Besides fundamental monotonic properties, the fatigue behavior of fiber-reinforced polymers plays an important role for structural applications in the aircraft industry. The design principle of “no-crack-growth” for the entire time in service is the current design rule for the application of CFRP in primary load-carrying aircraft structures in order to reduce the effort of maintenance [2]. The fatigue properties of CFRP as well as failure mechanisms were intensively investigated by e.g. Stinchcomb et al. [16], Reifsneider [17] and Talreja et al. [18] in the past decades. The results of enhancing fatigue properties of CFRP laminates by modifying the

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Nomenclature

$\sum_{n=1}^{N_f} \varepsilon_{a,p,n}$	cumulative hysteresis opening
σ_a	stress amplitude
$\sigma_f^{'}$	fatigue strength coefficient
b	generalized fatigue strength exponent
CAT	constant amplitude test
CFRP	carbon fiber reinforced polymer
CNT	carbon nanotubes
d′	cyclic damage exponent
$E_1/E_{1,0}$	stiffness degradation in 1-direction
f	frequency
FML	fiber metal laminates
GFRP	glass fiber reinforced polymer
HCF	high cycle fatigue regime
iCAT	interrupted constant amplitude test
IVW	Institute for Composite Materials (IVW GmbH) Kaiserslautern
LCF	low cycle fatigue regime
LIT	load increase test
MCFRP	metal- and carbon-fiber reinforced polymer
n′	cyclic hardening exponent
N_f	cycle numbers to failure
N_{limit}	ultimate number of cycles
R	stress ratio
TC	thermocouple
Δξ	change in magnetic volume fraction
ΔR	change in electrical resistance
ΔT	change in temperature
ΔW	plastic deformation energy
$\varepsilon_{a,p}$	plastic strain amplitude
$\varepsilon_{a,t}$	total strain amplitude

matrix system with carbon nanotubes (CNT) were shown e.g. by Knoll et al. [19] and Fenner et al. [20]. The potential of enhancing the fatigue properties by embedded steel fibers (MCFRP) was intensively investigated in [1]. In addition the application of the deformation-induced phase transformation of metastable austenitic steel fibers as an intrinsic damage sensor was introduced [1]. Past and present researches are dealing with the development of concepts for fatigue life prediction to reduce the effort of development and experimental characterization. Former investigations have tried to develop concepts for fatigue life prediction based on stiffness degradation models [21,22]. Brunbauer et al. tried software-based prediction of the fatigue life e.g. by using FEMFAT Laminate [23]. Further attempts used other material responses to tension-tension fatigue loads like strain measurements [24] or the change of electrical resistance [25]. The aim of the present study is the introduction of a time and resource-saving concept to analyze the fatigue behavior of polymer composites. Therefore, the current paper is focused on a new concept for fatigue life calculation based on cyclic load increase tests. A related method called PhyBal® was already and successfully applied for metallic materials by Starke et al. [26]. In principle S-N curves in the HCF-Regime can be described by Basquin's law, Eq. (1)

$$\sigma_a = \sigma_f^{'} \ * \ (2N_f)^b \tag{1}$$

Based on the correlations shown by Morrow [27] the fatigue strength exponent for metallic materials can be described by the following Eq. (2).

$$b = \frac{-n^{'}}{1 + 5n^{'}} \tag{2}$$

The equation describes the correlation between the fatigue strength exponent b and the cyclic hardening exponent n′. It is based on an empiric relation between applied stress amplitude and the total plastic strain energy to fracture. For most metallic materials the double logarithmic plot shows a slope of −0.25. In [27] a detailed explanation of this empiric relation is given and validated. However, the slope of −0.25 does not fit for composite materials and the cyclic hardening exponent n′ is based on local plasticity for metals. In case of polymer composites a damage accumulation and fatigue phenomenon is based on matrix cracks, interface decohesion and delamination of single plies, which leads to a negative slope of the S-N curve. So we propose to rename the exponent n′ to cyclic damage exponent d′. A detailed explanation will follow on how to develop the novel equation for the fatigue strength exponent and how it is applied to estimate the fatigue life of different polymer composite laminates.

2. Materials and specimen design

The two different types of composites used to introduce our new method for fatigue life prediction are a conventional CFRP laminate, which serves as reference and, the newly developed MCFRP laminate. The reference laminate is a 13-layered multi-axial CFRP with a typical aeronautical stacking sequence for fuselage applications, shown in Fig. 1.

The MCFRP combines a core of 13 pure CFRP layers with the same stacking sequence as the reference. 4 plies of metastable austenitic fibers occurring in bundles of 7 single steel fibers with a diameter of 60 µm are added by a filament winding process in the top and bottom layers (see Fig. 1). Table 1 summarizes the selected properties of both types of fibers used for reinforcement. The so called layer-separated approach provides mechanical advantages [23], compared to a homogenous distribution of steel fibers. In addition, enhanced electrical

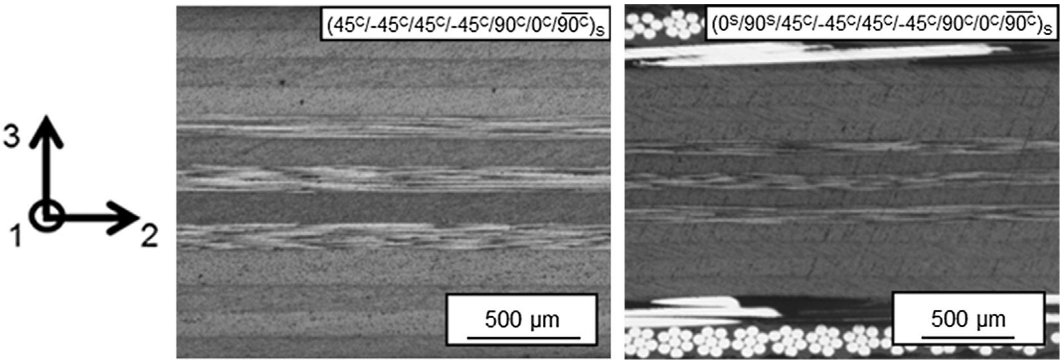

Fig. 1. Light optical micrographs of CFRP (left) and MCFRP (right) multidirectional laminate layups.