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FATIGUE PROPERTIES AND DAMAGE OF CF-PPS FROM HIGH TO VERY HIGH CYCLES

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ABSTRACT

Although fiber reinforced polymer composites (FRP) are increasingly used in primary aircraft structures, there is still a lack of knowledge on their fatigue behavior and underlying damage mechanisms, particularly under very high cycle fatigue (VHCF) conditions. To address these issues, there is a limiting factor regarding conventional fatigue testing concepts, as they are not capable of performing very high cycles (N > 100 million) in an economically feasible period. A unique ultrasonic fatigue testing facility was therefore developed for cyclic three-point bending of FRP. However, obtaining very high cycle fatigue data of polymer composites using elevated testing frequencies of 20 kHz is challenging with respect to the viscoelastic nature of polymers. In this research, therefore, energy dissipation by heat due to viscoelastic damping and interfacial friction was mitigated by compressed air cooling and pulse-pause control (1:20), resulting in an effective testing frequency of approx. 1 kHz. Furthermore, monitoring of suitable fatigue testing conditions was undertaken by infrared thermography, high-resolution force measurements and cyclic displacement control via Laser Doppler vibrometry. Nevertheless, low frequency benchmark tests were mandatory in order to evaluate data obtained by applying elevated testing frequencies. Therefore, cyclic three-point bending tests in the high cycle fatigue (HCF) regime were performed at 10 Hz for comparison. Besides investigating the fatigue behavior at lower cycle numbers than viable with the VHCF setup, the HCF tests allowed load frequency influences to be investigated and, thus, served as benchmarks for the ultrasonic VHCF experiments. To summarize, HCF and VHCF tests up to $2x10^9$ load cycles showed decrease of maximum bending stress versus fatigue life which could be described by separate power law functions for 10 Hz and 20 kHz testing frequency, respectively. Increased fatigue life was observed for 10 Hz compared to the 20 kHz testing frequency, yet, microscopic characterization indicated similar damage evolution and failure mechanisms in the areas of highest shear stresses.

1 INTRODUCTION

Carbon fiber reinforced polymer (CFRP) structures, e.g. jet engine fan blades or wind turbine blades are exposed to very high cycle numbers beyond 10^7, due to aerodynamic and gravitational loadings. Yet, VHCF data of fiber-reinforced polymers are scarce and fundamental knowledge is lacking on the specific fatigue properties of composite laminates, as well as the underlying VHCF damage mechanisms, due to extremely long testing times using conventional setups operating at frequencies up to 50 Hz. Data of the VHCF behavior of CFRP obtained by long-term experiments with frequencies from 0.1 to 157 Hz are given in [1-4].

In the present work, extensive investigations of CF-PPS in the VHCF regime up to 10^9 cycles [5, 6] were realized using a patented ultrasonic fatigue-testing facility for polymer composites [7], enabling cyclic three-point bending tests at 20 kHz in pulse-pause mode. With the resulting effective frequency of 1 kHz, 10^9 load cycles were reached within 12 days.

Cyclic three-point bending tests in the high cycle fatigue (HCF) regime were performed at 10 Hz for comparison. Since 10^9 load cycles would take more than 3 years, the 10 Hz tests were constrained to 10^7 load cycles in order to realize intersecting data of 10 Hz and 20 kHz tests.

The induced HCF and VHCF damage of the chosen carbon fiber 2/2 twill fabric reinforced polyphenylene sulfide laminate with orthotropic layup was characterized by light optical microscopy during interruptions and after fatigue failure. Additionally for the ultrasonic fatigue tests, the stiffness degradation was measured ex situ during interrupted fatigue tests.

2 MATERIAL AND EXPERIMENTAL SETUP

2.1 Composite material

Experiments were conducted on a carbon fiber twill 2/2 fabric reinforced polyphenylene sulfide (CF-PPS) manufactured by Bond-Laminates GmbH (Brilon, Germany). This composite, currently used in aerospace applications, is manufactured in cross-ply configuration with 19 plies, resulting in a laminate thickness of 4 mm. The twill 2/2 fabric contains HT-carbon fibers and has an area weight of 200 g/m². Since ultrasonic fatigue tests were carried out via resonance-based testing at 20 kHz, the specimen geometry was defined by modal analysis to 33.5 x 15 x 4 mm and a nodal distance of 18.7 mm to guarantee the first bending eigenmode to occur at 20 kHz. The FEM model was based on an orthotropic material behavior with nine elastic constants determined by tensile and bending tests according to DIN EN ISO 527-4, DIN EN ISO 14125, DIN EN ISO 14129 and DIN 65148, see Table 1.

Fibre volume content in %		55	Young's modulus in GPa	E_{11}	58.0
Mass density in g/cm³		1.55		E_{22}	58.0
Ultimate tensile strength in MPa	*11-dir.*	659±36		E_{33}	5.35*
	22-dir.	584±46	Shear modulus in GPa	G_{12}	3.16
Flexural strength in MPa	*11-dir.*	591±10		G_{13}	6.65
	22-dir.	604±17		G_{23}	6.65
Shear strength in MPa	*12-dir.*	42.2±0.4	Poisson's ratio	ν_{12}	0.04*
	13-dir.	37.7±0.7		ν_{13}	0.10*
	23-dir.	35.4±0.5		ν_{23}	0.10*

*Values estimated based on literature [8]

Table 1: Selected material properties of CF-PPS.

2.2 Experimental setup

For the VHCF experiments, the abovementioned ultrasonic fatigue testing system was applied in three-point bending configuration (Fig. 1). All VHCF experiments were displacement controlled, in pulse pause mode (1:20), i.e. at an effective frequency of ~1 kHz and stress ratios of $0.21<R<0.51$. For the ultrasonic fatigue tests, a constant mean stress of 115 MPa was chosen for all stress amplitudes to achieve sufficiently high maximum stresses, since the displacement amplitude was limited due to the oscillating frequency of 20 kHz. Therefore, the stress ratio of the VHCF tests is varying.

Cyclic deflection was measured by Laser Doppler vibrometry and specimen surface temperature was monitored by infrared thermography. Further details of the ultrasonic fatigue testing facility are given in [5]. The damage behavior was characterized by light optical and scanning electron microscopy on the polished side surfaces of the specimens.

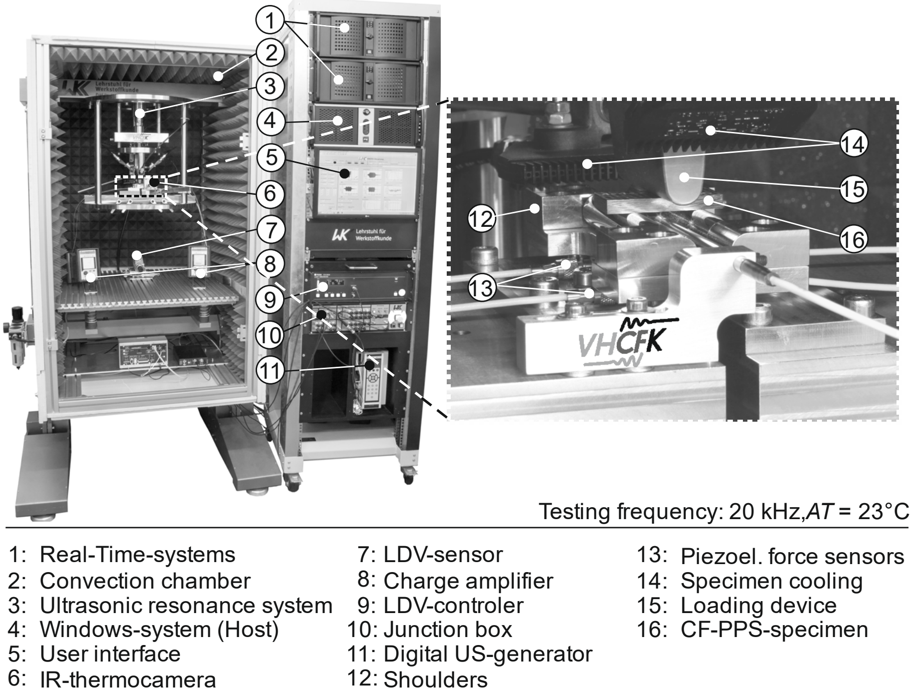

Figure 1: Ultrasonic testing facility for cyclic three-point bending at 20 kHz, according to [5].

A Schenck Hydropuls PSA 10 servohydraulic testing system, depicted in Fig. 2, was used for three-point-bending HCF tests with sinusoidal waveform at f = 10 Hz and a stress ratio of R = 0.21. This R value was chosen to resemble the stress ratio of the ultrasonic fatigue tests at the highest investigated stress amplitudes. A capacitive displacement sensor with a sensitivity of 10 V/mm was employed for deflection measurement of the load-controlled tests at 10 Hz in the servo hydraulic setup. In addition to the stiffness degradation calculated from changes in deflection, specimen temperature monitored by infrared thermography was used as a further indicator of fatigue damage accumulation.

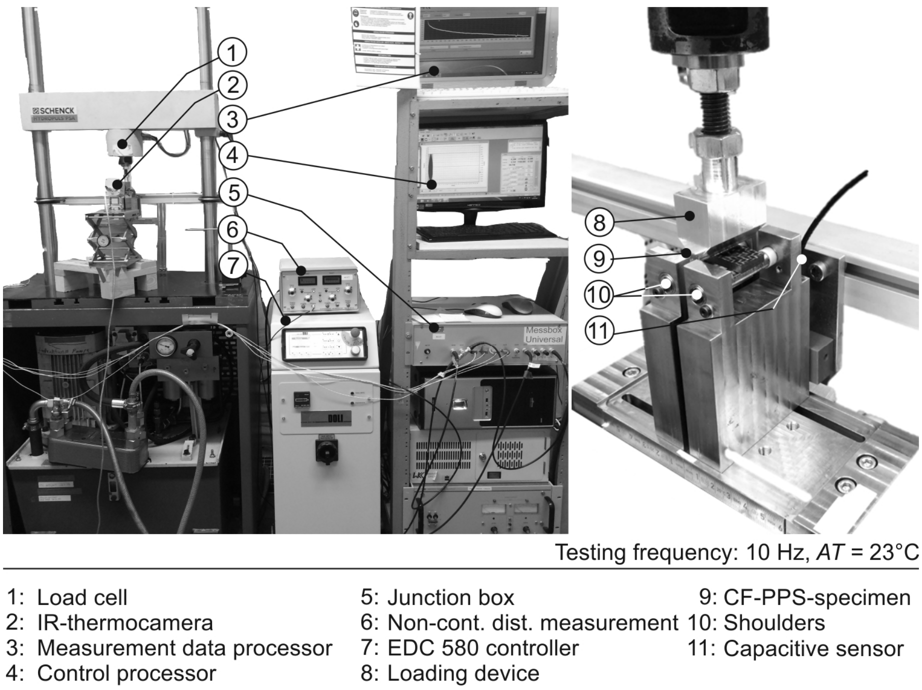

Figure 2: Servohydraulic PSA 10 testing facility for cyclic three-point bending of CF-PPS at 10 Hz.

3 EXPERIMENTAL RESULTS

3.1 Constant amplitude tests in the HCF and VHCF regime

The HCF and VHCF lifetime behavior obtained by both, fatigue testing at low (10 Hz) and ultrasonic frequencies (20 kHz), is summarized in Fig. 3 where the maximum cyclic flexural stress $\sigma_{max,11,(initial)}$ is plotted versus the number of cycles to delamination N_{Del}. Due to fundamental differences in the fatigue testing facility, the stress calculation of $\sigma_{max,11,(initial)}$ was realized as a function of experimental setup. Whereas monotonic stress for the ultrasonic fatigue tests was calculated based on Hooke's law for orthotropic materials with ε_{11} determined by strain gauges and the experimentally obtained elastic constants mentioned in section 2.1, the dynamic strain measurements during ultrasonic fatigue loading were carried out using 3D-scanning vibrometry based on high resolution video triangulation combined with very fine measuring grids [9]. The stress calculation of the experiments carried out at the servohydraulic testing system was realized by classic beam theory containing the specimen geometry and shoulder distance as well as the maximum applied force. According to the displacement controlled 20 kHz and the load-controlled 10 Hz tests, $\sigma_{max,11,initial}$ and $\sigma_{max,11}$ is plotted, respectively. The specimen failure of the VHCF experiments at N_{Del} was determined by macro-delaminations along with the loss of bending resonance caused by a shift of the eigenfrequency due to stiffness degradation. Subsequently, self-heating due to increased internal friction between crack surfaces led to a rise of temperature up to 50 % of T_g at which time the fatigue tests were aborted. Within the stiffness degradation investigations discussed in section 3.2, selected CF-PPS specimens were characterized. An average stiffness loss of 12 % was determined after failure according to the abovementioned criteria. Hence, this value was also used as failure criterion to define the number of cycles to delamination N_{Del} for the load-controlled 10 Hz benchmark tests.

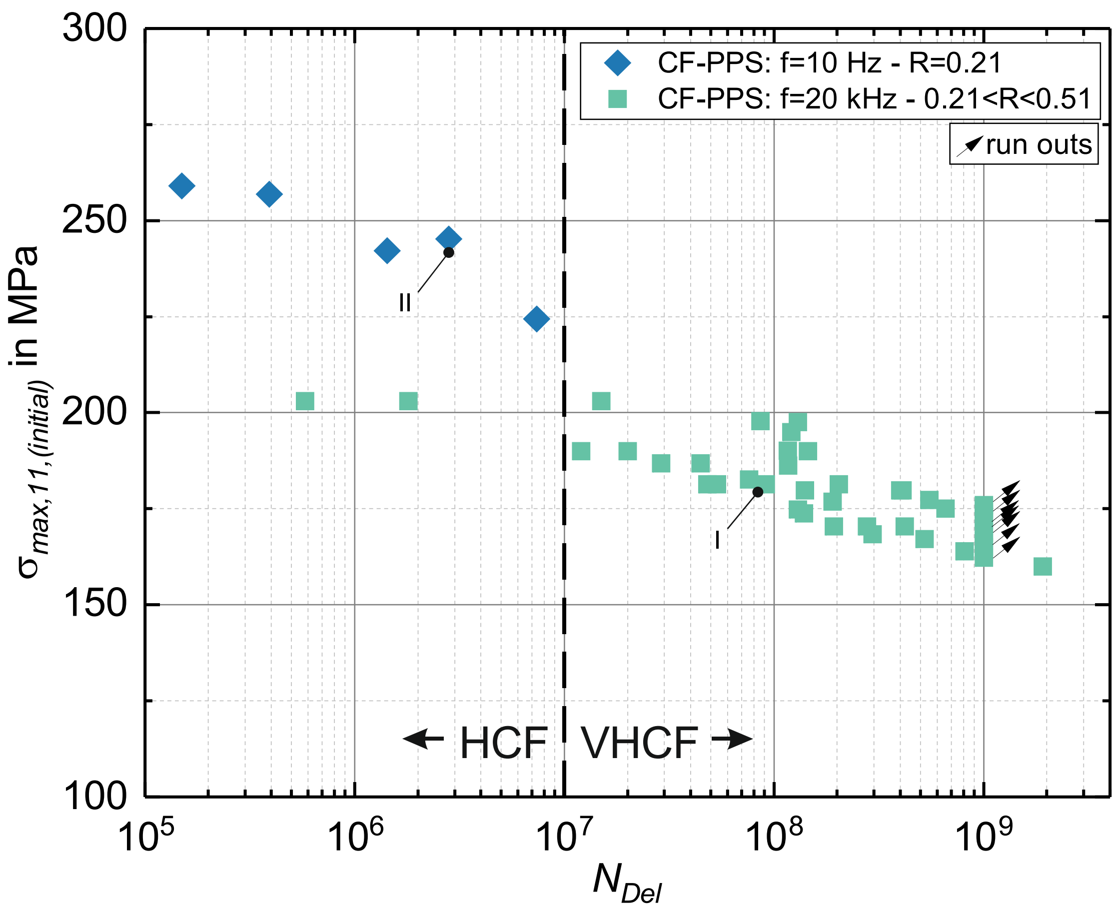

Figure 3: $\sigma_{max,11,(initial)}$ - N_{Del} curve for constant amplitude loading of CF-PPS in the HCF and VHCF regime.

No endurance limit exists for the VHCF tests up to $2x10^9$ cycles under the applied loading conditions, yet, a fatigue strength at 10^9 cycles of $\sigma_{max,11}$ = 162.2 MPa was determined. Furthermore, the results indicate an increased fatigue life for the lower testing frequency of 10 Hz compared to the ultrasonic fatigue tests seemingly traceable to self-heating as a result of elevated strain rates. It should be noted that neither dynamic stiffening at high frequencies nor damping capacity reduction was considered so far. These questions remain substance of ongoing research.

3.2 Stiffness degradation of HCF and VHCF loaded CF-PPS

The stiffness degradation of selected specimens was measured ex situ during interrupted ultrasonic fatigue tests. Each data point of the stiffness degradation plot represents the mean value of five measurements at the same specimen. Because of negligible scatter, standard deviation was not depicted. The measured residual stiffness values were referred to the initial stiffness $S_{b,x,0}$ determined before each VHCF experiment. Representative degradation curves of the normalized specimen's stiffness $S_{b,x}/S_{b,x,0}$ versus the normalized number of cycles to delamination N/N_{Del} for CF-PPS were plotted beside the characteristic degradation curve for the 10 Hz tests in Fig. 4. Due to the lower frequency, the stiffness degradation could be monitored in situ by continuous load and displacement measurement without any interruptions during the 10 Hz tests.

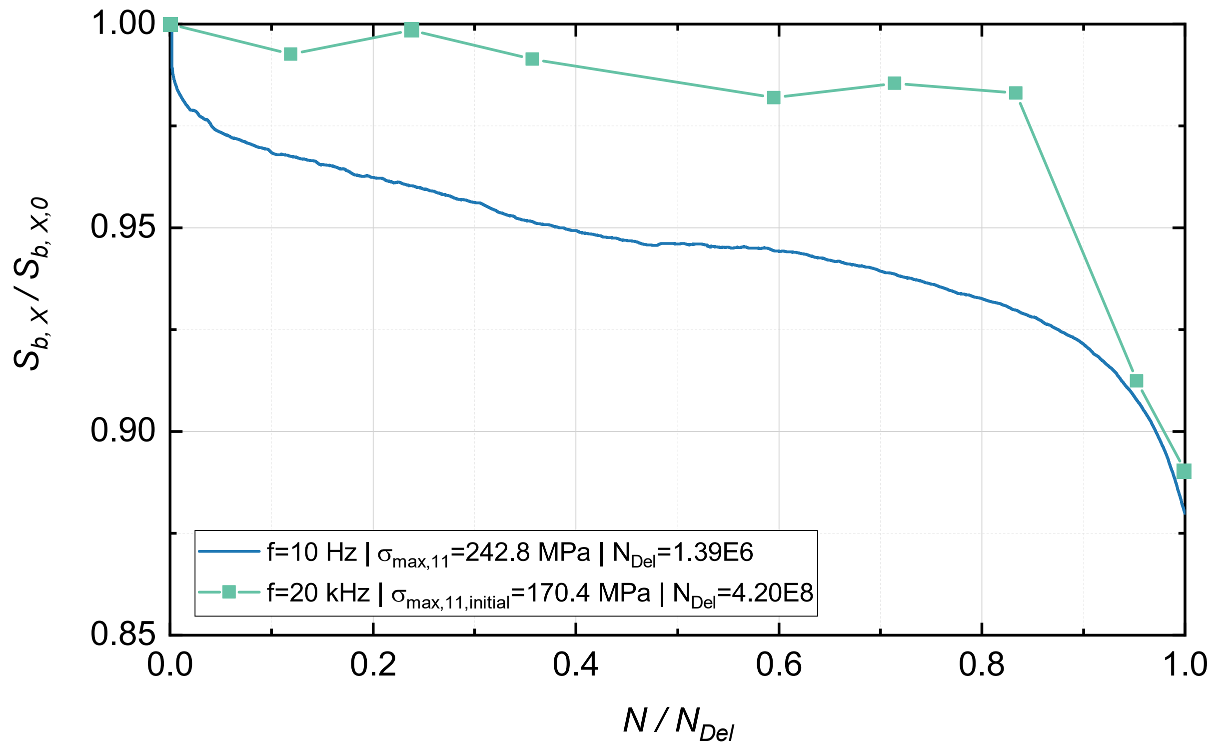

Figure 4: Characteristic specimen stiffness degradation of CF-PPS under HCF and VHCF (interrupted fatigue tests) loading.

CF-PPS specimens tested at a frequency of 20 kHz showed an initial stiffness degradation of about 5 % up to 82 % of N_{Del} caused by fiber-matrix interface failure and transversal cracks in the area of the specimen where highest shear stresses occurred. Subsequent damage progression was characterized in terms of meta-delaminations starting at about 80 % of N_{Del} and followed by macro-delaminations. Furthermore, the ultrasonic tests of CF-PPS resulted in an average absolute stiffness loss of 12 %. In particular, the extent of meta-delaminations in CF-PPS led to a significant stiffness degradation, yet maintained a temperature level below 40° C within the very first cycles after the appearance of initial meta-delaminations. The most significant difference between the two degradation curves is the stiffness loss of 5 % within the first 5 % of N_{Del} of tests conducted at 10 Hz. This occurred because the absolute maximum stress was about 30 % higher and, therefore, fibre-matrix interface failure as well as transversal cracks accumulated faster. Additionally, both curves showed a characteristic slope shift at 80-82 % of N_{Del} accompanied by meta-delaminations and subsequent macro-delaminations.

3.3 Microstructural failure mechanisms of HCF and VHCF loaded CF-PPS

Light optical investigations were performed to characterize the fatigue failure mechanisms and were carried out in the case of specimen failure at N_{Del}, or after reaching the ultimate number of 10^9 cycles (VHCF) and 10^7 cycles (HCF), respectively. The damage mechanisms in the HCF and VHCF regime were similar, as can be seen exemplarily in light optical micrographs of crack networks on the side face of a specimen at the end of life at 20 kHz (Fig. 5-left) and 10 Hz (Fig. 5-right), respectively. The specimens correspond to the labels I/II in Fig. 3. In both cases, failure of the investigated CF-PPS occurs in the areas of highest shear stresses due to beam aspect ratio and fiber-matrix interface properties. Compared to an investigated epoxy-based system [10], weak interface properties could be observed as adhesive interface failure occurred, and served as the origin of further crack growth. The microscopically detected failure mechanisms as well as the damage progression coincided for 10 Hz and 20 kHz and, therefore, no shift of mechanisms due to elevated testing frequencies could be determined.

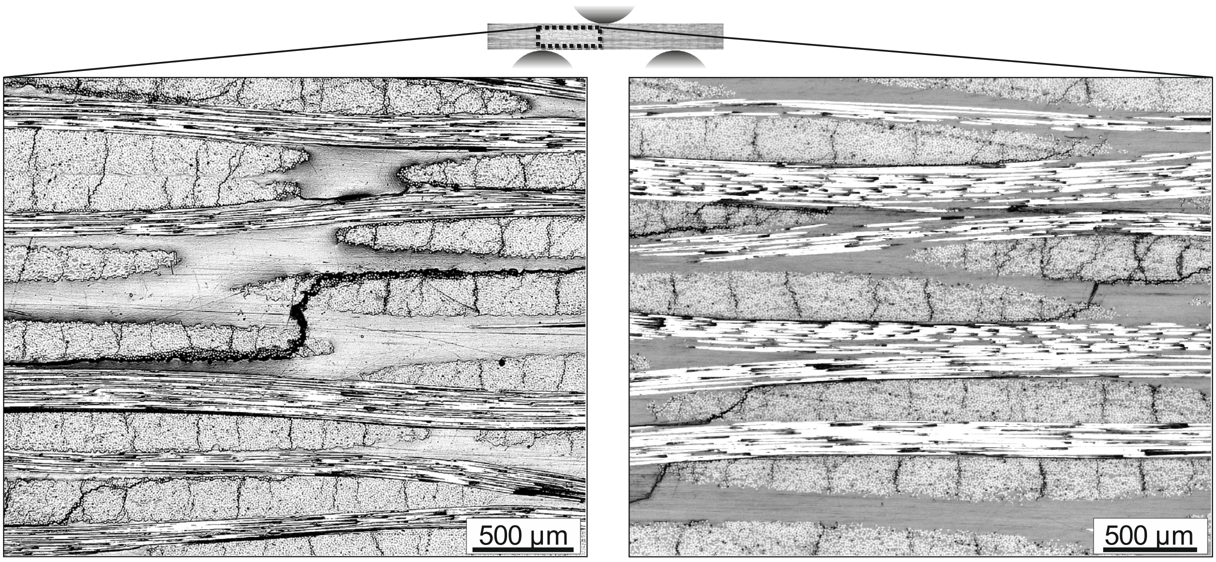

Figure 5: Optical micrographs of specimens fatigued in the VHCF range at N_{Del}=9.1E7, $\sigma_{max,11,initial}$=181.4 MPa and 20 kHz (left, acc. to labeled specimen I in Fig 3) and in the HCF range at N_{Del}=2.68E5, $\sigma_{max,11}$=260.2 MPa and 10 Hz (right, acc. to labeled specimen II in Fig 3).

The damage progress of the CF-PPS laminate is characterized by different fatigue damage states starting with fiber-matrix debonding in the 90° rovings at the very beginning of the HCF and VHCF experiments, followed by transversal cracks in the 90° rovings, leading to intra-ply micro-delaminations between 0° and 90° rovings. The subsequent typical fatigue state was induced by so-called inter-ply micro and meta-delaminations. These meta-delaminations grew to macro-delaminations across several plies resulting in the specimen's delamination failure at N_{Del}. Due to the initial fiber-matrix debonding in the shear-stress dominated areas, the fiber-matrix interface seems to have had the lowest resistance against fatigue-induced crack initiation. Furthermore, no fatigue damage due to tensile or compression loads could be detected in the scope of the current experiments. Further details and results of the damage progress and the failure mechanisms of CF-PPS are described in [5, 6]. The interface properties are key aspects of very high cycle fatigue failure, as the most critical stress state especially at low stress amplitudes for initial damage is the fiber-matrix interface. These properties determined the location of the transverse crack initiation and were also observed as precursors to other damage types such as debonding-induced matrix cracking and delaminations.

4 CONCLUSIONS

The HCF and VHCF behavior of aircraft qualified carbon fiber twill 2/2 fabric reinforced polyphenylene sulfide was systematically investigated up to 10^9 loading cycles at 20 kHz and up to 10^7 loading cycles at 10 Hz, respectively. To perform the VHCF experiments in an economically feasible timeframe, an ultrasonic fatigue testing facility for cyclic three-point bending was used. 3D laser scanning vibrometry measurements were carried out to analyze the strain distribution and realize stress calculations. The fatigue experiments at 10 Hz and 20 kHz resulted in a significant decrease of the bearable maximum bending stress of CF PPS in the range between 10^5 to 10^9 loading cycles and, therefore, no endurance limit existed under the applied loading conditions. A fatigue strength at 10^9 cycles of $\sigma_{max,11,initial} = 162.2$ MPa for CF-PPS under cyclic three-point bending at 20 kHz was determined. A decreased fatigue life for elevated testing frequencies at 20 kHz was found in spite of analogous fatigue failure mechanisms at both testing frequencies. The fatigue damage was characterized by progressive damage accumulation in the highest shear-stressed areas, consistent with the literature. In ongoing research activities, frequency influence is being studied in more detail by frequency-temperature superposition (FTS) mastercurves, 100 Hz benchmark tests and alternative non-crimp carbon fiber reinforced composite systems.

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