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Experimental investigation of the very high cycle fatigue of GFRP $[90/0]_s$ cross-ply specimens subjected to high-frequency four-point bending

T.J. Adam *, P. Horst

Institute of Aircraft Design and Lightweight Structures, Technische Universität Braunschweig, D-38108 Braunschweig, Germany

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ABSTRACT

In contrast to low cycle and high cycle fatigue, very high cycle fatigue of fibre-reinforced composites has only been explored in part. Knowledge of degradation behavior, damage mechanisms and phenomenology of damage initiation and growth in the range up to 10^8 cycles and beyond is rare. A special high-frequency four-point bending test rig has been set up to circumvent common problems such as specimen heating. As tests can be conducted in a frequency range between 50 and 80 Hz, load cycle numbers of up to 10^8 are reached within acceptable testing times. In the presented test series, the very high cycle fatigue behavior of a $[90/0]_s$ glass fibre-reinforced laminate is tested at six different load levels. The use of online transmitted light photography and stiffness monitoring provides the correlation of stiffness degradation with transverse cracking and delamination. The effect of load level is examined. Damage growth differs for high- and low load levels. At low loads, degradation is shifted to higher cycle numbers. Delamination onset is delayed by slower crack growth in thickness direction. At the lowest loads, cracks initiate marginally indicating a threshold for transverse cracking in fatigue.

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1. Introduction

Due to their superior material properties, fibre-reinforced plastics (FRP) have found their way into modern lightweight structures in all fields of application. As the majority of structures made from FRP has to withstand vibrant, cyclic, highly dynamic or quasi static interval loads, fatigue has been investigated since the 1960s. Today, a broad knowledge is available for cycle numbers ranging from static failure via low cycle fatigue (LCF) to high cycle fatigue (HCF). Beside SN-behavior, also fatigue damage, its underlying mechanisms as well as resulting stiffness and strength degradation have been comprehensively investigated by many authors [1–6]. In addition to uniaxial and multiaxial in-plane loadings, out-of plane load cases have been focused as well. Several studies on bending fatigue of unidirectional [7], cross-ply [8,9] and other configurations [10–12] including woven and hybrid materials can be found in literature. However, with respect to fatigue life, several applications face even higher cycle numbers in the so-called very high cycle fatigue (VHCF) range beginning at 10^8 cycles. Typical examples are the rotor blades of wind turbines (due to service time) and fan or compressor blades of aircraft engines (due to frequency). Although there is a strong need, the very high cycle fatigue of FRP has not been sufficiently investigated yet [13]. The main reason for this is that testing at standard frequencies requires very long testing times. A 10^8 cycle test for example takes about 116 days at a frequency of 10 Hz. Unfortunately, as polymers show relatively high material dampings, an increase of frequency results in undesired specimen heating. A possible workaround pursued in literature is to use very thin specimens of thicknesses about 1 mm. In doing so, Mandell et al. [14–16] conducted first comprehensive tests of wind turbine blade materials under the auspices of the U.S. Department of Energy's (DOE) Wind Energy Program. Most tests were constant-amplitude cyclic stress against cycle to failure (SN) tests of thin test coupons. Additionally to SN-behavior, Hosoi et al. [17–21] investigated the effect of load level on transverse cracking and delamination. According to Hosoi et al., tensile load amplitudes below 30% of the average static tensile stress shift failure into the VHCF range. Furthermore, the order of appearance of transverse cracking and delamination changes. At laminate stresses lower than 20% of the static strength, no damage at all is found up to 2.0×10^8 cycles. Another recent approach to VHCF, utilizing a shaker-based test rig, is presented by Gude et al. [22].

One finding which is crucial for the acceleration of cyclic tests is that fatigue does not depend on frequency, as long as the specimen temperature is kept low. This has been commonly stated by Mandell et al., Hosoi et al. and Apinis [23].

* Corresponding author.
E-mail address: tj.adam@tu-braunschweig.de (T.J. Adam).

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Trying to circumvent specimen heating, this publication presents an alternative test method for testing FRP at elevated frequencies. Regarding the testing equipment, a specialized test rig has been developed [24,25]. A first experimental investigation of the onset and progression of transverse fatigue cracks and the resulting loss in bending stiffness has already been presented for a $[90/0]_s$ laminate [26]. An extended investigation including the initiation and growth of interlaminar delamination as well as its dependency on the load level is presented in this work. Furthermore, the existence of a threshold for transverse cracking is explored.

2. Experimental set-up for high-frequent VHCF testing

Numerous difficulties are faced and several requirements have to be met when testing at elevated frequencies [14]. In addition to the extensive heating there are other side-effects. As axial testing of unidirectional laminates leads to high forces, self-fatigue of standard servo-hydraulic machines is a common problem. Further difficulties are raised by the load application (delamination and heating of doublers) and the damage monitoring (e.g. failure of strain gauges). Thus, a test rig circumventing the main difficulties has been set up [24,25]. Its basic idea is that not stressing all laminate sections equally solves the heat transfer problem. In other words, bending, which mainly stresses exterior layers by tension, compression or both is a favorable load case for VHCF-testing. In pretests [25] alternating four-point bending turned out to be the most promising load case. The main benefit is the constant bending moment between the middle pair of the bearings. Damage grows uniformly in this constantly stressed region. Furthermore, temperature rise is well below 15 °C relative to ambient temperature for cross-ply layups. Besides the regulation of the ambient air temperature (20 °C ± 1.5 °C), no additional cooling is required. However, there are difficulties as well. As bending requires rather large deflections (up to ±5 mm), high accelerations have to be continuously maintained. This is a major problem for most actuator systems containing large inner moving masses (for example shaker actuators). Therefore, a customized electrodynamic system is used.

An overview of the main mechanical test rig components is given in Fig. 1. A single independent VHCF unit can be seen on the left. It is driven by means of an electrodynamic actuator which allows non-resonant testing at frequencies of up to 80 Hz. A two-sided ($R = -1$) light-weight four-point bending device clamping a flat bending specimen ($[t, w, l]_{spec}$ = [2, 25, 82]mm, 80 mm bending length) is detailed on the right. Rotable polymer trunnions prevent frictional heating and abrasive specimen damage. With the middle part being deflected by the actuator, a sinusoidal bending load is applied. Loads and deflections are measured online by means of two load cells and a laser triangulator. A control circuit in *NI Lab View©* provides force or displacement control. Concerning the damage monitoring, online techniques (all techniques which do not require specimen removal) are preferred. Due to the bending forces being rather small compared to typical loads of axial tests, bending tests are sensitive to variations in specimen positioning. Thus, three online monitoring systems have been integrated into the test rig (Fig. 2). With the total amplitude of force $f_a = f_{a1} + f_{a2}$ and the deflection d_a being detected continuously throughout the test, a simplified dynamic effective (secant) bending stiffness $\bar{E}_{xb}$ can be calculated by means of the four-point bending equation and the geometric parameters (a = 20 mm, b = 40 mm) depicted in Fig. 3:

$$\bar{E}_{xb} = \frac{f_a}{d_a} \frac{6}{w_{spec} t_{spec}^3} \left(\frac{1}{3} a^3 + \frac{1}{2} b a^2 + \frac{1}{8} a b^2 \right) \quad (1)$$

This approach is based on several assumptions. Regarding the overall approach, the first order beam theory is assumed to be valid for damaged materials, as long as the damaged continuum can be homogenized. This is typically done by means of unit cell approaches and has also been proven for partial cracks (definition see Section 4) by Schmitz and Horst [27]. Another aspect is the geometric type of beam. With a width-to-thickness ratio of w_{spec}/t_{spec} = 12.5 the beam can be considered as a wide beam only showing a curvature along the specimen axis κ_x. Anticlastic bending is assumed to be negligible $\kappa_y = \kappa_{xy} = 0$. A further simplification concerning $\bar{E}_{xb}$ (indicated by the bar) results from the fact that damage growth is not uniform along specimen length. In specimen regions a, damage decreases towards the specimen ends. This means that $\bar{E}_{xb}$ does not reflect the stiffness of the uniformly damaged central region (E_{xb}) accurately. The error of this method has been assessed by means of quasi-static experiments and analytical considerations [28]. It has been found that the degradation of the maximum stressed middle part dominates the overall stiffness loss. In fact, with fatigue damage growing regularly in regions a, $\bar{E}_{xb}$ only deviates slightly from E_{xb}.

In the course of the test, the amplitude of deflection increases along with specimen degradation due to force control. Fig. 3 shows exemplary plots of forces (constant), deflection (increasing) and bending stiffness (decreasing).

In addition to stiffness monitoring, two optical systems allow the phenomenological examination of the damage mechanisms.

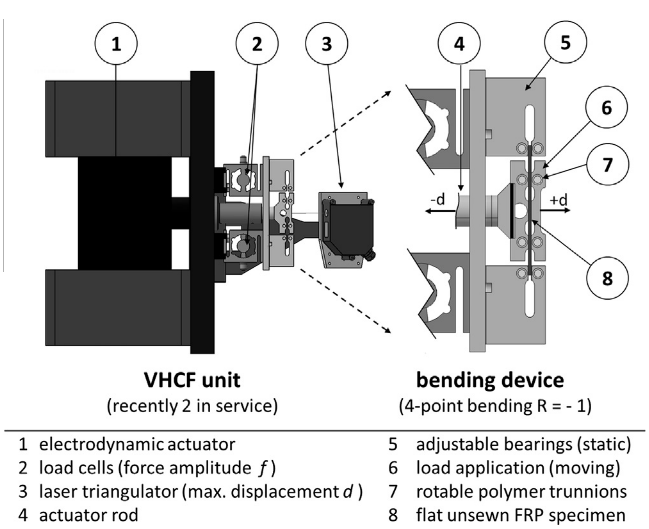

Fig. 1. Schematic diagram of a VHCF unit and the four-point bending device.

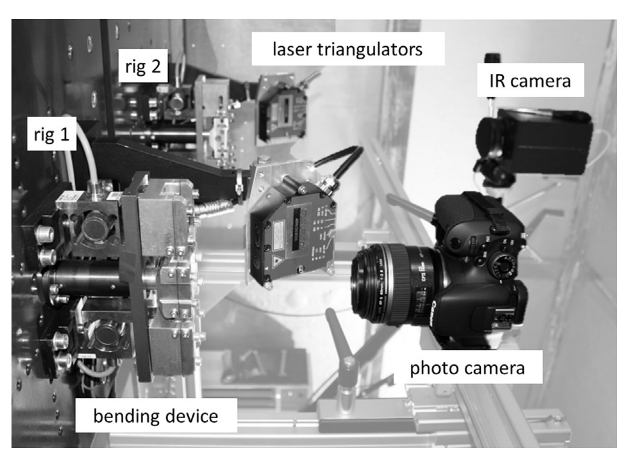

Fig. 2. Overview of the VHCF four-point bending test rig.

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