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Guided bending experiment for the characterisation of CFRP in VHCF-loading

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ABSTRACT

The effective experimental characterisation of the damage and failure behaviour of polymer based composites under VHCF-loading depends directly on the development of reliable accelerated fatigue test methods. Here, a guided-bending fatigue experiment in forced excitation is proposed. Key requirements are: high frequency fatigue without significant warming of the specimen, homogeneous stress distribution, widely automated control and in situ crack determination.

Using analytical and experimental investigations, a significant improvement of the test stand design, reported earlier [1] has been found in the form of a shaker based bending test stand with kinematically guided displacement. Improvements in the area of durability, homogeneity of the stress state, repeatability of the test and control have been achieved.

1. Introduction

Carbon fibre reinforced polymers (CFRP) are predestined for applications in lightweight structures under static and cyclic loadings. The failure behaviour of CFRP has been under investigation since the 1960s. In the field of fatigue loading, standardised tension and bending fatigue tests up to 10^7 cycles are widely used for material characterisation [2–4]. Here, the maximum test frequency is limited to about 20 Hz due to internal heating of the polymer matrix. In practice, many fibre reinforced structures, such as wind turbine blades, are loaded to more than 10^8 cycles [5]. Analogous to metals, where changing crack initiation behaviour in this cycle range is labelled differently, the fatigue range is called very high cycle fatigue (VHCF). Common fatigue experiments with test frequencies up to 20 Hz do not lead to satisfactory results in the VHCF regime within a reasonable test time, but higher test frequencies well above 20 Hz lead to significant warming and undesired premature failure of the specimen [6].

The complexity of an experimental setup for loading frequencies above 20 Hz and the complex damage behaviour of CFRP may be the reasons for the lack of well-founded knowledge of the VHCF-fatigue degradation behaviour and appropriate material parameters.

Since 2010, the priority program SPP 1466 “Infinite Life for Cyclically Loaded High Performance Materials”, funded by the German research foundation (DFG) in 17 separated projects, aims at the description and modelling of the VHCF behaviour of different materials on different scales. Within project 5 “Failure mode related calculation models for the life prediction of continuous fibre reinforced nanoparticle modified polymers in the VHCF-regime”, the development of adapted test principles for the characterisation of the VHCF phenomena for non-crimped carbon fibre reinforced composites is one main aspect.

1.1. General test principle and procedure

The main obstacle in high frequency testing of CFRPs is internal heating. For the reduction of damping induced heating in test stand design, low shear deformation and small loaded volumes are advisable. Several researchers recently followed these assumptions by developing VHCF-bending fatigue test stands. Backe et al. developed an ultrasonic bending fatigue test stand in 3-point-bending configuration [7]. A very high testing frequency of 20 kHz was achieved. Due to the required stiffness of the specimen for achieving a first eigenmode at 20 kHz, a comparably short and thick specimen has to be used. Together with the 3-point-bending configuration, this results in an intra-laminar shear stress dominated fatigue experiment with significant internal heating. By the

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use of pulse-pause sequences and active cooling, the specimen temperature was successfully controlled.

Adam et al. published a test stand design based on 4-point-bending and electrodynamic excitation where external cooling or pulse-pause sequences are not required [6]. Here, the homogeneous bending stresses between the two shoulders are used for investigating the transverse cracking on the bottom and top surfaces. The key factor in this development is the electrodynamic excitation system providing comparably large displacement amplitude at testing frequencies of about 80 Hz.

The test principle developed here is based on shear force free bending according to Fig. 1. A slender and layered bending specimen is restrained by ball joints and loaded with an eccentric mass *m* and a spring *c*. The setup is excited by a forced oscillation with a shaker system. In Ref. [1] a test stand based on this concept has been presented first. Due to fixed ball joints on both ends of the bending test stand, it could be used for small deflections only. To overcome this limitation, a significantly improved VHCF test stand with an additional degree of freedom in the direction of the specimen length has been designed by applying kinematically guided specimen clamps. Using analytical and experimental investigations, the design process and its result are highlighted here.

2. Improved VHCF-test stand design

2.1. Analytical optimization

For realising fatigue experiments with the given test principle, a recently developed kinematic approach is adopted [8]. Here, Modler et al. used the deformation kinematics of Bernoulli beams under shear force free bending for the gear synthesis of a guidance mechanism providing the motion of the beam ends during deformation. The guidance mechanism can specifically be optimized, up to a certain positioning error e_{max}, to guide the x-y position and rotation angle of the bending specimen clamping for a wide range of bending deformations. Hence, the typical axial sliding of the specimen on the classical test support is avoided completely and the specimen is forced geometrically into the desired deformation.

In Ref. [8] it is concluded that mechanisms with a straight lined centrode are suitable for providing the complex motion for introducing shear force free bending in rectangular specimens. According to [9], every mechanism with a basic link and a constant ratio of $i = 2$ provides the straight centrode. The most suitable mechanisms for fatigue testing have been found in the form of planetary gear sets according to Fig. 1. Two possible configurations can be proposed, one with a sun and a planetary wheel (fixed-moving) and another with two fixed gears with the rotational degree of freedom only (fixed-fixed). From a kinematics point of view, both configurations are identical. Solving a three position optimization problem regarding the guidance error, the linkage geometry can be determined for providing the plane motion and rotation of the clamping according to the desired shear force free bending of the specimen.

It has been found that the resulting mechanisms are not inevitably symmetrical regarding the *y*-axis. By introducing the axis of symmetry at $y = 0$ as an additional boundary condition, which is a necessity for alternating bending experiments, the problem is reduced to a two position optimization problem.

The analytical gear synthesis for the focussed VHCF bending test stand is performed by defining:

- the specimen length to 65 mm,
- an axis of symmetry at $y = 0$ and
- the first position at $\phi_1 = 0°$ rotation.

Then, the synthesis is applied for two varying positions. Positions one and two fulfil the exact motion positions in displacement x, y and angle ϕ for shear force free bending of the specimen. According to Fig. 2, the mean guidance error between ϕ_1 and the maximum desired rotation ϕ_{max} (20° in the fixed-moving

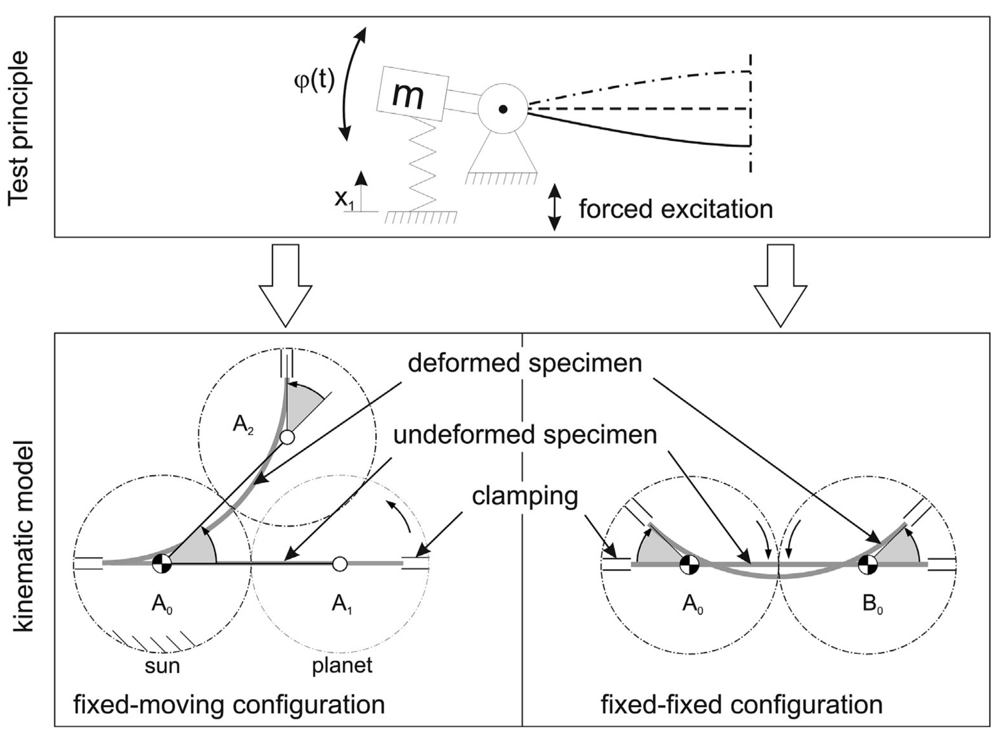

Fig. 1. Planetary gear sets for fatigue testing application, test principle, fixed-moving (left) and fixed-fixed (right) configuration.