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Air-coupled guided waves combined with thermography for monitoring fatigue in biaxially loaded composite tubes

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ABSTRACT

Non-destructive methodologies for remote monitoring of fatigue induced by mechanical load in fibre reinforced plastics are presented. Hollow cylinders (glass fibre winding) were stepwise biaxially fatigued and measured in single-sided access configurations. Based on conversion of air-coupled ultrasound to guided waves, it is shown that accumulated fatigue damage is accompanied by decrease in phase velocity and increase in attenuation. The change in wave velocity caused by fatigue is shown to correlate closely with measurements of stiffness degradation of the composite. The attenuation of guided waves is affected by crack density which is visually traceable in the transparent composite. Monitoring of cyclic loading of the specimens by thermal imaging and a high-speed camera revealed that the initiation of final failure in the specimens coincides with spots of increased temperature. Air-coupled guided wave area scans allow for observing the development of these areas and other local damage in the composite.

1. Introduction

The global demand for polymer-matrix composites in various industries has been rising enormously due to their high specific strength and stiffness. The performance of fibre reinforced plastic (FRP) is affected by material degradation resulting from mechanical loads. Fatigue damage is particularly important in applications (aircraft, wind energy) where the components encounter many loading cycles during their lifetime.

Mechanically induced fatigue in FRP reveals several damage mechanisms (matrix cracking, delamination and fibre fracture), which correlate with stiffness degradation [1,2]. Fatigue damage in composites can be divided into three stages. During the initial stage (I), matrix cracks develop in plies loaded orthogonally to the fibre orientation, which leads to a rapid decrease in stiffness. Stage (II) is characterized by a slight quasi-linear decrease in stiffness and the development of a critical damage stage (saturation of matrix cracks) with initial local delaminations caused by transverse cracks. The last stage (III) includes consolidation of local delamination and fibre cracking, which results in catastrophic failure. The hollow cylinders investigated in this study enable cyclic loading with arbitrary load ratios between tension/compression and torsion. This geometry without free edges is adequate to simulate fatigue damage formation in commonly employed FRP components.

For non-destructive detection of fatigue-induced defects, innovative methodologies are needed to secure functionality and avoid unnecessary replacement of components. Several techniques (acoustic emission, electric resistivity, optical fibres etc.) have been proposed for detection and characterization of fatigue damage in FRP caused by cyclic loading. Each of the techniques comes along with its drawbacks such as expensive sensors for structural health monitoring using smart structures or challenging application in industrial environment.

The correlation between the area of highest temperature (hot spot) during cyclic loading and the location of final failure was revealed using thermography [3]. The development of hot spots indicates a material state close to failure. Thermography was applied to the study presented to complement the investigations.

Conventional ultrasonic technique for probing material stiffness and its degradation involves direct measurements of bulk wave velocities [4]. However, this methodology requires an immersion bath and two-sided access, which impedes *in situ* application. Furthermore, the data obtained in this transmission mode are often not applicable to fatigue monitoring in strongly heterogeneous composite materials.

Guided waves in tubes behave similarly to Lamb waves for certain ratios between wall thickness, radius and wavelength [5]. Lamb waves are two dimensional guided waves travelling in plate-like structures. They offer a convenient method for recovering in-plane elastic properties [6,7]. Contact Lamb wave setups were found to be applicable to monitoring stiffness degradation in FRP induced by thermal and mechanical ageing [8–10]. It was

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shown that the attenuation is sensitive to cracking induced by fatigue for a circumferential wave propagating in hollow FRP cylinders [11].

Air-coupled ultrasound (ACU) has been increasingly used for inspection of plate-like components in recent years due to its advantage of being a non-contact and non-immersion methodology [12]. The conventional normal transmission mode has been modified to provide mode conversion of air-coupled ultrasound to Lamb waves for remote non-destructive evaluation in a single-sided access configuration [13]. A similar technique was recently applied to measuring phase velocity and attenuation for testing moisture content and micro cracking in carbon fibre reinforced plastic [14]. Air-coupled Lamb wave imaging was also used to detect local defects like delaminations in composites [15].

In this paper, the ACU mode conversion is applied to the study of guided wave velocity and attenuation in cyclic loaded composite cylinders (tube winding). It is shown that these parameters correlate with stiffness degradation and crack density. Local modification/damage in the composite observed with ACU is compared to thermal imaging and visual inspection. It is shown that theses techniques allow for monitoring of fatigue in FRP induced by mechanical loads.

2. Materials and specimens

The specimens used during these investigations were nominally defect-free wound tube specimens made of E-glass–fibre rovings (Owens Corning, type OC111A). They were produced by a winding machine, which enables manufacturing of arbitrary lay-ups. As in previous research [11], the specimens consist of 8 layers with a symmetric lay-up of [0°/45°/90°/−45°]S. For this work, the relative mass fractions of the layers were 49% (0°), 23% (45°), 5% (90°), and 23% (−45°). Together with a common resin/hardener-combination (RIM135/RIMH137) the wound tube specimens were manufactured by using resin transfer moulding (RTM) with the inner and outer 0°-angled plies being parallel to the axial direction of the tube specimens. The mechanical properties of the materials are presented in Table 1.

The tested specimens were tubes of 46 mm diameter and 330 mm length with approximately 2.0 mm thickness and a fibre volume fraction of about 50 %. In further production steps, both ends of the tube specimens were reinforced by glass–FRP-doublers of 70 mm length and bonded steel inserts which prevented failure caused by the fixing pressure of the testing machine.

The advantages of the wound tube specimens are the possibility to apply biaxial loads (combination of tension/compression and torsion) with arbitrary load ratios and to prevent the so-called free-edge effect which occurs under fatigue loading using flat specimens. Due to different fibre orientations in the plies, the selected lay-up promises high intra- and interlaminar stresses throughout cyclic loading resulting in development of matrix cracks.

3. Experimental setup and analysis

The experiments were arranged to allow for inducing fatigue damage accompanied by non-destructive testing. The fatigue experiments were accomplished with a servo-hydraulic tension–torsion machine. The circular clamping of this testing machine enabled testing of the described tube specimens. All fatigue tests were performed in a force-controlled manner with $R = -1$ and a frequency of 3 Hz. R describes the ratio between the minimum and maximum stress σ during one fatigue cycle, as follows:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}. \qquad (1)$$

Furthermore, different biaxial load ratios were investigated, whereas the biaxiality ratio (parameter β) is defined as:

$$\beta = \arctan\left(\frac{\tau}{\sigma}\right). \qquad (2)$$

Thereby, the angle between shear stress τ and tensile/compressive stress σ indicates the different biaxial load cases. Four different load cases were chosen for experiments, whereas the biaxiality ranges from pure shear ($\beta = 90°$) to pure tension/compression ($\beta = 0°$). The other load cases are $\beta = 30°$ (combination of tension/compression and torsion with the tension/compression part being dominant) and $\beta = 60°$ (also combination of tension/compression and torsion with a predominant shear part). The loading directions and magnitudes are listed in Table 2.

The fatigue tests were divided into three repetitive steps:

1. *Characterization step*: In order to monitor the material stiffness, quasi-static tests were conducted with force-controlled ramps (pure discrete tension/compression force and positive/negative torsion moments). These loads were considerably smaller than the applied fatigue loads and chosen in such a way that the load was adequate for calculating the Young's and shear modulus.
2. *Fatigue damage step*: Cyclic loads (sinus wave form) with constant amplitudes and different biaxial load ratios were performed to introduce fatigue damages like matrix cracking, delaminations and fibre failure. During each fatigue damage step, thermographic monitoring was applied for locating the final failure in an early stage of fatigue life. Furthermore, a photo camera was used for observing the qualitative development of cracks and for recording the final fatigue fracture (high-speed-mode with 60 pictures per second).
3. *ACU measurement and crack monitoring*: In order to observe the damage mechanisms the fatigue test was stopped after several fatigue steps and the specimen was taken out of the testing machine. The ACU measurements (Section 4) were conducted in this phase of the fatigue test. Online thermal imaging often indicated imminent failure so that the fatigue step was stopped to achieve ACU measurements just before failure. The matrix cracks, which are the first type of damage occurring, were studied using an optical microscope due to the transparency (similar refraction index of glass fibre and resin) of the specimen. Photos of several different areas of the tube were taken and used for crack counting. The cracks observed were aligned along the fibre direction of each ply. Differentiating the cracks by their orientation angle leads to the number in each layer which was referred to the size of the digital picture to calculate the crack densities presented in this work.

For exact measurements with the thermography camera, a constant ambient temperature of 20 °C is required. This was assured by a cooling chamber installed between the grips of the testing

Table 1
Mechanical parameters of the materials.

Fibre OC111A	
Young's modulus	80.7 GPa
Tensile strength	2.56 GPa
Density	2.58 g/cm^3
Resin/hardener L135i/ H137i	
Tensile modulus	3.2–3.5 GPa
Tensile strength	70–80 MPa
Compression strength	120–140 MPa
Elongation at rupture	5.0–6.5%
Density	1.18–1.20 g/cm^3
Glass transition temperature	90 °C