Evaluation of Fatigue Damage in Composites with Various Defects Using Air-coupled Guided Waves

Martin RHEINFURTH 1, Frank SCHMIDT 2, Richard PROTZ 3, Gerhard BUSSE 1, Peter HORST 2, Maik GUDE 3, Werner HUFENBACH 3

1 Institute for Polymer Technology (IKT), University of Stuttgart, Stuttgart, Germany; Phone: +49 711 685 62669, Fax: +49 711685 62066; email: martin.rheinfurth@ikt.uni-stuttgart.de, gerhard.busse@ikt.uni-stuttgart.de
2 Institute of Aircraft Design and Lightweight Structures (IFL), Technical University of Braunschweig, Braunschweig, Germany; frank.schmidt@tu-bs.de, p.horst@tu-braunschweig.de
3 Institute of Lightweight Engineering and Polymer Technology (ILK), Technical University of Dresden, Dresden, Germany; r.protz@ilk.mw.tu-dresden.de, m.gude@ilk.mw.tu-dresden.de, ilk@ilk.mw.tu-dresden.de

Abstract
Based on mode conversion from ultrasound in air to guided waves, tubes made of glass fibre reinforced plastic are investigated in a single-sided access configuration. Fatigue damage is induced by biaxial mechanical loads in specimens with and without defects. Using the proposed non-contact methodology, porosity, low velocity impact damage, and fibre waviness are detectable before cyclic loading. During fatigue loading, damage formation resulting in ultimate failure and effects of defects are monitored by air-coupled guided wave area scans. The observed decrease in guided wave velocity correlates closely to stiffness degradation of the composite due to cyclic loading. Increase in guided wave attenuation corresponds to development of crack density being visible in the transparent composite. Early initiation of delamination due to porosity and fibre waviness are detected using the non-contact ultrasound setup. The initiation spot of ultimate failure is in many cases predictable depending on existence and type of pre-damage.

Keywords: Guided waves, composite, fatigue, effects of defects, fibre waviness, impact damage, porosity, air-coupled ultrasound

1. Introduction

In times of sustained globalisation and growing environmental problems, resource-conserving mobility and renewable energies gain in importance. Rising demand for transportation of passengers and goods raises growth of civil aerospace and similar industries. However, arising scarcity of fossil energy sources and essential climate protection force reduction in structural weight to minimize fuel consumption. This reduction can be accomplished using fibre reinforced polymer (FRP) because of its high specific stiffness and strength. The advantages of FRP including simplified manufacturing processes also explain its application in the area of renewable energies, as production of rotor blades for wind energy plants.

Increasing usage of FRP challenges non-destructive testing (NDT). Detection of the large variety of defects occurring in heterogeneous and anisotropic polymer-matrix composites during their manufacturing process and operation requires advanced non-destructive evaluation (NDE). For example, fatigue damage of metals is characterised by nucleation and growth of a single crack, which is detectable using conventional penetrant or eddy current testing. In comparison, fatigue mechanisms of (frequently non-conducting) FRP involve many different defects and more complex accumulation of damage. NDT of composites is highly relevant because fatigue damage induced by typical cyclic loading of aircrafts or wind turbines reduces residual strength and stiffness of structural components. Detection and monitoring (during service) of manufacturing or operation induced defects is important to evaluate their detrimental effect on structural integrity and fatigue resistance.
After an overview on fatigue damage and defect kinds in composites, a short literature survey on exemplary NDT methods for damage evaluation is presented. This paper focuses on the principle of air-coupled guided waves which is outlined referring to existing literature. Excerpts of recent research outcomes obtained by using this technique are presented.

2. Fatigue damage and types of defects in composites

Mechanical induced defects in composites can be categorised in delamination, matrix crack, and fibre fracture. A delamination in FRP is characterised by debonding of two plies with different fibre orientations. Matrix cracks often occur as transverse cracks: a single ply is prone to crack through its entire thickness parallel to the fibres due to mechanical loading orthogonal to its reinforcement direction. Failure of a large number of filaments in one ply is considered as fibre fracture.

Reifsnider [1] distinguishes between three stages of fatigue damage evolution in FRP under tension fatigue loads which also applies for tension-compression loads [2]. The first stage is characterised by formation of transverse cracks resulting in a steep drop in Young’s modulus of the FRP. The second stage of fatigue damage evolution involves crack consolidation and development of small delaminations on the tips of transverse cracks which is accompanied by only little stiffness degradation. Due to formation of large delaminations and fibre fracture, stiffness rapidly decreases in the last stage of fatigue life till ultimate failure.

Bird strike, hailstorm, and tool drop are classic hazards for structural components made of FRP. The resulting impact damage is often undetectable by visual inspection of the outer component surface even though an impact may result in large internal delaminations and decrease in fatigue life [3]. An unavoidable feature of large FRP parts is porosity which has a detrimental effect on fatigue performance depending on void distribution and void volume content [4]. Besides porosity, also excessive fibre waviness is a common manufacturing induced defect leading to early formation of delamination and ultimate failure under fatigue loading [5].

3. Review on NDT methods for various defects in FRP

The geometry of a delamination in composites can be readily characterised by various NDT techniques such as thermography with optical excitation [6], speckle interferometry [7], defect resonance [8], conventional ultrasound c-scans, and many more. Single matrix cracks and very small delaminations, however, are hardly detectable using the above mentioned methodologies. Thermography with ultrasonic excitation detects matrix cracks close to the specimen surface [9]. Penetrant enhanced x-ray radiography can be used for detection of matrix cracks and small delaminations [10]. However, radio-opaque liquid penetrates only in cracks connected to the surface, which limits inspection to laminates with only a few layers and consolidated cracks. Reduction in ultrasonic amplitude measured in pulse-echo configuration correlates with increase in matrix crack density [11]. The attenuation of ultrasound waves is also used to determine the volume content of voids [12]. Fibre fracture and delamination events can be monitored using acoustic emission [13]. Characterisation of fibre waviness in FRP components is a challenging issue, which is tackled using ultrasonic waves [14] and terahertz NDE [15].
Lamb waves velocities in plate-type FRP components can be used to monitor stiffness degradation induced by fatigue loading [16]. Attenuation measurements of circumferential guided waves in tubes excited by contact transducers correlate with crack density and stiffness degradation [17]. Using air-coupled ultrasonic transducers, Lamb wave assessment can be performed in a non-contact and single-sided configuration [18]. Area scans with air-coupled Lamb waves are suited to detect delaminations [19]. This paper summarizes and compares recent investigation in the area of air-coupled guided waves for fatigue monitoring involving FRP tubes with and without pre-damage [20-22]. Furthermore, preliminary research results involving porosity are presented [23]. The differences in area scans of typical defects as impact damage, fibre waviness, and void accumulation are discussed. The effect of mechanical fatigue loading on the results of area scans is introduced. The correlation of guided wave velocity and attenuation, Young’s modulus degradation, and matrix crack density is illustrated by an exemplary specimen without pre-damage. The effect of defects on this correlation is outlined referring to the literature [20-23].

4. Experimental approach

Filament winding and resin transfer moulding (RTM) was used to manufacture tubular specimens made of glass fibre reinforced plastic (GFRP) [20]. Fibre waviness was introduced by low thread tension during the winding process, which led to deviation of position and orientation of the rovings (fibre bundles) close to the outer surface of the tube [21]. Variation of the RTM process parameters and air injection are used to accomplish evenly distributed and accumulated porosity, respectively [23]. For the investigation of impact related pre-damage a polyamide projectile was shot on the specimen [22]. Fatigue damage was introduced in the GFRP tubes (wall thickness: 2 mm; diameter: 46 mm) by a servo-hydraulic biaxial testing machine. This allows for the study of damage formation resulting from a combination of reversed normal loads (tension-compression) and reversed shear loads (negative-positive torsion). Young’s modulus of the tubes was calculated from data obtained by the hydraulic testing machine [20].

The specimens were repeatedly removed from the test rig after a certain number of cycles for NDE. Commercial air-coupled ultrasound transducers with a centre frequency of 207 kHz and an active diameter of 8 mm were used to excite guided waves in the tubes [20]. The generated guided mode is akin to the lowest antisymmetric plate wave (a0-mode). The ultrasound radiated from the guided wave was detected by a receiving transducer to measure phase and amplitude. In order to calculate phase velocity and attenuation, the propagation distance of the guided wave was varied by moving the receiver away from the stationary transmitter. Area scans of the tube wall were performed by keeping the distance of the two transducers constant while rotating and translating the tubular specimen. Crack densities, delamination shapes, and porosity distribution were characterised by visual inspection of the transparent GFRP [20-22].

4. Comparison of result excerpts for tubes with and without defects

Thick rovings as compared to wall thickness and resin accumulations between the rovings cause a quite uniform stripe pattern in the area scans for nominal flawless regions of the tube [20]. This consistent pattern of straight stripes is disturbed in areas of fibre waviness (Figure 1). Over the full length of the tube between 90° and 240° of the circumference, patterns of wavy and interrupted stripes indicate deviation of roving positions and orientations. During fatigue loading, this results in early and excessive delamination along wavy rovings which
was detected by area scans and confirmed by visual inspection [21]. High speed imaging revealed that always one of the observed delaminated areas leads to ultimate failure.

Size and shape of impact-induced delamination is definable by air-coupled area scans because of high amplitude deviation and missing stripe pattern (Figure 2). Even the depth distribution can be estimated by phase area scans [22], which was asserted by visual inspection. Fatigue loading resulted in some cases in growth of delamination being detectable by area scans before all specimens started to fail in the area of the impact damage.

![Figure 1. Area scan of tube with fibre waviness before fatigue loading (colour bar indicates deviation in percentage from arithmetically averaged amplitude) [21]](image1)

![Figure 2. Area scan of tube with impact induced delamination before fatigue loading [22]](image2)

Areas of high void concentration can be identified by sudden intensity and width variations of the typical stripes (Figure 3, position: 60 mm, 120°). In contrast to the observed wavy stripes caused by fibre waviness, however, the stripes remain straight. Latest results imply that critical void accumulations, which lead to delamination during cyclic loading, appear in the area scan. The onset of catastrophic failure was always located in one of the delaminated areas. Very recent results indicate that specimens with finely distributed porosity display features which look very much like those obtained on nominal defect-free specimens. These porosity specimens also exhibit similar fatigue behaviour. More detailed results will be presented in an upcoming journal article [23].

Fatigue damage of nominal flawless tubes includes development of spots with accelerated degradation process which are detectable using thermography during cyclic loading [20] and air-coupled guided waves between the fatigue steps (Figure 4). The deviation image between the area scans after 95.6% and 98.7% reveals three of those spots. Comparison of area scans disregards the inherent inhomogeneity of the GFRP (stripe pattern) and shows more clearly the evolution of fatigue damage than a single air-coupled scan. A high speed camera disclosed that the most obvious spot (position: 120 mm, 100°) initiated final failure of the specimen [20].

The guided wave attenuation rises by about 40% throughout fatigue life in the presented data (Figure 5). However, more data published in [20] shows that the heterogeneity of this particular filament winding composite and resulting inhomogeneous fatigue evolution affects the attenuation results. The increase in attenuation is caused by scattering on matrix cracks and small delaminations. Within the first 15% of loading cycles till final failure, 90% of
matrix cracks develop (Figure 5). In addition to crack consolidation, the formation of delamination on tips and intersections of transverse cracks explains the incline in attenuation even after crack saturation. The rapid formation of matrix cracks corresponds to the steep drop in Young’s modulus and guided wave velocity in the first 15% of fatigue life (Figure 6). Gradual decline in velocity and stiffness till ultimate failure of the tube are in good agreement. Since locally limited accelerated fatigue evolution insignificantly affects the overall stiffness of the comparable large specimen, progressive stiffness degradation just before final failure (as reported in [1, 2]) is absent. More experimental data about damage evolution monitored by air-coupled guided waves including various loading conditions is presented in [20].

Compared with nominal defect-free GFRP tubes, less fatigue damage was observed for specimens with fibre waviness or impact damage till final failure. Outside of the pre-damaged areas, matrix crack formation is interrupted before saturation by early ultimate failure of the specimen. The same applies to stiffness degradation and decrease in guided wave velocity [21, 22]. The effect of the investigated porosity is currently being studied. Porosity with low volume content seems to have only a small influence on the investigated fatigue indicators [23].
5. Conclusions

NDE based on air-coupled guided waves allows for detection and characterisation of accumulated voids, (impact-induced) delamination, and excessive fibre waviness in GFRP tubes. These three different types of pre-damage are readily distinguishable in single-sided access configuration by means of area scanning. Guided wave area scans can also monitor evolution of fatigue damage unaffected and affected by initial defects. If not hidden by formation of a large delamination, the initiation spot of ultimate failure is most often predictable towards the end of the specimen’s lifetime. The air-coupled configuration with variable transducer distance is well suited for velocity and attenuation measurements of guided waves even in rather heterogeneous composites. The observed phase velocity and attenuation data is a useful measure of fatigue damage including stiffness degradation and matrix crack density. The presented non-contact methodology, which is most likely applicable to all kinds of FRP and shell-type structural components, is a versatile indicator for manufacturing and operation induced damage.

Acknowledgements

The authors gratefully acknowledge the support by the German Research Foundation (DFG) as part of the project PAK267.

References

23. F Schmidt, M Rheinfurth, P Horst, and G Busse, 'Multiaxial fatigue behaviour of GFRP with evenly distributed or accumulated voids monitored by various NDT methodologies', Submitted to International Journal of Fatigue.