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Degradation monitoring of impact damaged carbon fibre reinforced polymers under fatigue loading with pulse phase thermography

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ABSTRACT

Carbon fibre reinforced polymers were subjected to impact damage and fatigue load in tension–compression. During fatigue the development of the defects was monitored with pulse phase thermography using optical excitation. The development of phase angle difference measured between damaged areas and undamaged areas of the specimen shows a similar behaviour as degradation curves based on the variation of the material's modulus. Additional investigations with ultrasonic c-scans, radiography and microscopy show correlations between the phase angle difference change and the accumulation, initiation and growth of delaminations, cracks and the geometrical dimensions of these defects.

1. Introduction

Increasing use of carbon fibre reinforced polymers (CFRP) in aeronautical applications calls for non-destructive testing methods capable to detect relevant defects which occur during the service life of a part. Especially aircraft maintenance requires a fast, contact free and large area measurement technique to tackle the enormous variation of complex part geometries at an economically and practically acceptable level. Numerous testing methods such as ultrasound, shearography and thermography [1–4] offer themselves. Ultrasonics, an established technique in maintenance of aircraft yields precise results concerning the size and depth of a defect. However, contact during testing is required and the testing is comparably time consuming if the system is not optimized for a specified part geometry. Methods such as active thermography or air coupled ultrasound on the other hand allow contact free, fast and large area non-destructive inspection, where the focus of this study is on active thermography.

In the past various thermography testing and evaluation protocols such as lock-in thermography [1,5,6] or pulse phase thermography (PPT) [7,8] have been developed. Lock-in thermography uses a modulated excitation, inducing thermal waves into the material where the contrast of the resulting image is given either by the signal magnitude or by the phase of the thermal wave. Phase images are independent of surface features and yield a higher depth range improving the measurement's detection limit and interpretation of results. Thermal waves are reflected at discontinuities, such as delaminations or cracks, which when within the detection range of the infrared (IR) detector, lead to a change in the thermal field on the part's surface [1,5,6]. Depending on excitation frequency features in various depths can be detected, however, leading to an increased measurement time. To overcome this, Maldague et al. proposed PPT where measurement time is reduced without losing the advantages of a lock-in evaluation. For PPT the excitation form is a rectangular pulse which is decomposed to a multitude of sinusoidal components with different frequencies using a Fourier transform. This way, magnitude and phase images are obtained for various excitation frequencies and accordingly depths with one measurement [7,8]. Recent investigations in the field of thermography focus e.g. on automatic defect detection and classification based on IR image characteristics. Usamentiaga et al. use edge detection and clustering, convex hulls, active contours for automatic defect detection [9] and shape and amplitude feature extraction for classifiers to determine impact energies [10].

Investigations on CFRP under fatigue load have shown the simultaneous occurrence of several consecutive damage mechanisms. Strong correlations are found between stiffness reduction and the development of defects, thus allowing grouping of different damage mechanisms into three characteristic stages during fatigue life [11–13]. In tension–tension loaded cross-ply laminates initial stiffness reduction is attributed to transverse crack formation until the characteristic damage state and transverse crack saturation is reached at the end of stage I. In stage II the formation of longitudinal cracks in the vicinity of transverse cracks predominates. At intersections of transverse and longitudinal cracks

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additionally small delamination formation is observed. The final damage mode, longitudinal splitting, is initiated in stage III where entire parts of the 0° plies are detached from the remaining laminate due to longitudinal crack and delamination growth. Both transverse and longitudinal cracks lead to fibre fracture due to stress concentrations at the crack tip or induced shear stress due to kinking at crack bridging zones [14]. In tension–compression loading a steeper slope in S–N curves is found. This is attributed to buckling of the outer plies in the vicinity of delaminations and transverse cracks under compressive load leading to delamination growth. Additionally, the described damage mechanisms under tensile loads apply. The initiation of transverse cracks is, however, faster as the debonding between fibre and matrix, advancing the transverse crack formation initiates and propagates more rapidly under compressive loads [15].

During the service life of a structure it is highly likely it will be subjected to impact damage. In the case of an aircraft this could be due to ground vehicles, hail, bird strike or tool drop during maintenance. Accordingly, the fatigue behaviour of composites after impact damage has been investigated extensively in the past. Especially in the compressive loading regime where buckling in the vicinity of delaminations occurs, impact damage leads to shorter life [16–18]. Due to the impact damage the statistical spread of the cycles to failure for each load level increases [17]. Especially for thin laminates a flattening of the S–N curve's slope is observed [18]. Impact damage evolution under compressive fatigue load leads to growth of the delaminations opposite to the impact site in loading direction and transverse to it as well as to buckling of strips around the damage zone [16,19–21]. Larger accumulated damage in the impact zone leads to a stronger decrease of lifetime [16] and rapid delamination growth is usually an indication of imminent failure [19]. For an investigation of damage growth methods such as radiography and ultrasound c-scan are suitable [16,18,19]. Disadvantageous of these methods is that they require a stopping of the test and removal from the fixture. This process is prone to flaws in the testing procedure as the effect cannot be quantified, neither has it been investigated systematically yet. Rheinfurth et al. observed steps in the measured stiffness curves over cycles, when specimen were removed from the test fixture and propose a method to monitor in situ with the specimen still clamped in the fixture where only loading had to be stopped [13]. Chen et al. presented an impressive solution by using acoustography for in situ monitoring of the damage during loading. However, the experimental set-up is rather elaborate as testing has to be conducted in a water tank included in the testing machine [20,21]. Toscano et al. used optical lock-in thermography to measure delamination growth during quasi-static compressive loading. Besides delamination growth also an increase in phase contrast between defective areas and the sound panel was observed. This was attributed to higher delamination openings due to compression induced local buckling [22]. Ultrasonic and optical excited thermography has been employed to detect fatigue damage, namely delaminations and matrix cracks in interrupted fatigue tests [23,24]. Both techniques allowed a detection of fatigue induced cracks, where the results obtained with optical excitation were less clear than the ultrasonic excitation [23]. Fibre–matrix debonding, advancing transverse cracks, cannot be detected with most conventional NDT methods but requires advanced methods such as X-ray refraction topography [25]. Additionally, theoretical and numerical calculations show that fibre breakage influences the thermal conductivity and thus results obtained from thermography [4]. Furthermore, damage accumulation during fatigue can be correlated with the surface temperature which increases with the amount of energy dissipated at defects [26–28]. Garnier et al. investigated the damage growth of impact damage during fatigue loading using one optical excited thermographic NDT image which was processed with temperature images obtained during fatigue loading. It was found that both damage growth and stiffness reduction correlated [29] and were well in line with the model described by Jamison et al. [14].

Despite numerous experimental works, no links between thermal resistance change and mechanical damage are available in a form which allows to link the thermal response of a material to distinct damages [4]. Moreover, most studies on interrupted tests with thermographic inspections show only few measurements per specimen thus impeding a correlation of thermographic signal characteristics and damage states.

In this paper a method to monitor in situ damage growth and accumulation during fatigue loading with active thermography is presented. The aim is to contribute to a better understanding of how and to what extent different present damages, such as delaminations, inter fibre fracture and fibre rupture affect thermography data. For this, the phase angle difference is related with phenomenological observations of damage mechanisms based on ultrasonic, X-ray and microscopy measurements.

2. Experimental procedure

2.1. Specimen preparation

The specimens were manufactured from a carbon fibre Cycom 977-2-35-12 k HTS prepreg with a $[0/90]_{4s}$ lay-up. During lay-up the laminates were compacted every four layers in the stacking sequence by applying a vacuum for 15 min. Curing was realised in an autoclave at 177 °C for 3 h with a pressure of 7 bar to obtain a void free laminate with T_g of 212 °C. 1 mm thick and 50 mm wide aluminium and glass fibre reinforced polymer (GFRP) tabs were adhered to the cured laminates with UHU® plus endfest 300 at 60 °C for 1 h, with the GFRP between the laminate and the aluminium tabs. The fibres in the GFRP tabs were oriented in ±45° direction. From the manufactured plates specimens with the dimensions $250 \times 35 \times 2\ mm^3$ were machined with a free specimen length of 150 mm. Deviance of specimen width from test standards is attributed to the necessary width to accommodate for impact damage where delaminations do not reach the specimen sides and the maximum loading capability of the testing machine. Specimen sides were polished with up to 1000 grain size abrasive paper to avoid edge effects.

Impact damage was introduced with a drop weight tower. A photo sensor activating a clamp ensured anti-rebound after the first impact. Contact force was measured with a strain gauge full bridge included in the semi-spherical striker. All impact damaged specimens were subjected with 3.8 Joule impact energy.

2.2. Fatigue testing

Fatigue testing was conducted with a servo-hydraulic Instron/Schenk 100 kN fatigue test machine with hydraulic clamps at a stress ratio of $R = -1$. Clamping pressure was set according to loading forces. To avoid buckling in the compressive loading regime the specimens were put in an anti-buckling guide with a long hole ($28 \times 80\ mm^2$) in the middle. This way global buckling of the specimens is avoided while local buckling in the area of delaminations can still occur allowing for a delamination dominated failure as expected for the lay-up and loading case [30]. For strain measurements a laser extensometer from Fiedler Optoelektronik GmbH was used. Two strains were transmitted to the evaluation software WAVE MATRIX from Instron, yielding two measured stiffnesses, one between the marker bars one and four (global stiffness) and one between the markers two and three (local stiffness) (Fig. 1). For the degradation curves only the stiffness measured between