NON-CONTACT ULTRASOUND FOR SINGLE-SIDED DETECTION OF FATIGUE AND DEFECTS IN COMPOSITES

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Abstract
This paper presents a non-destructive technique for both remote monitoring of fatigue induced by mechanical load and detection of delaminations induced by low velocity impacts in fibre reinforced plastics (FRP). The methodology is based on mode conversion of air-coupled ultrasound to guided waves. The variation of guided wave velocity indicates the fatigue state of specimens made of non-crimp glass fibre fabric: our experiments demonstrate that accumulated fatigue damage is accompanied by a velocity decrease of the guided wave mode which corresponds to stiffness degradation of the composite. Further experiments show that the single-sided access configuration allows also for evaluation of size and shape of impact induced damage in tubes made of carbon fibre reinforced plastic (CFRP).

1 Introduction
The amount of FRP has been rising immensely in various applications (aviation, wind energy, etc.) for the last two or three decades. The properties of FRP are affected by structural degradation caused by many factors like damage due to impact or fatigue. Fatigue damage is particularly important for applications where the components are exposed to many load cycles, which may result in internal accumulation of damage in the composite. Three stages of fatigue in multiaxial laminates need to be distinguish: the first 10-20% of fatigue life (phase I) is characterized by a steep decline in stiffness due to a rapid increase of matrix cracks. This is followed by a moderate decrease in stiffness accompanied by formation of local delaminations (phase II). Consolidation of delaminations and fibre rupture within the last few percent of the lifespan (phase III) signalizes approaching final failure. Beside fatigue damage, impact induced defects (tool-drop, hail, etc.) may reduce the structural integrity of FRP components [4]. Innovative non-destructive methodologies for monitoring composite degradation in operation need to be investigated to guarantee functionality and to avoid unnecessary replacement of components. Optical lock-in thermography provides reliable results for detecting and sizing of impact damage in CFRP [5]. However, this technique fails for monitoring of matrix crack formation and stiffness degradation due to cyclic loading. The “stress wave factor” being related to ultrasound attenuation has been used for evaluation of fatigue and impact damage in composites [6]. This methodology brings along the drawback of complex coupling of the transducers to the component or the need for structure-integrated sensors. In this work, a recently developed methodology based on air-coupled guided waves [7, 8] is applied to evaluation of typical composites and common types of damage such as impact and fatigue.

2 Experimental Methodology
Fig. 1 illustrates the single-sided access configuration used for air-coupled generation and detection of guided waves in FRP. The angle of excitation and detection θ of ultrasound is chosen according to the phase matching conditions for the investigated guided wave mode [9]:

$$\sin \theta = \frac{v_a}{v_g}$$

(1)

where $v_a$ and $v_g$ are the phase velocities of ultrasound in air and of the plate wave mode, respectively. The value of $\theta=17^\circ$ corresponds to the maximum output signal that is found by varying the angular positions of the transducers. Air-coupled ultrasound transducers from Airstar Inc. with an aperture of 8 mm were used at a frequency of 200 kHz. Guided wave velocity is determined from the relation of signal output phase and the distance.
between transducer and receiver. Therefore, a Discrete Fourier Transformation (DFT) of the output signal is performed every 1 mm when the receiver distance increases from 20 mm up to 70 mm. The guided wave velocity depends on plate thickness, ply lay-up, ultrasound frequency, density, and material stiffness of each ply [10]. As a rough rule of thumb, a decrease of material stiffness results in a drop in guided wave velocity.

A scanning device which rotates and translates the tubes was used for imaging the specimen’s surface while maintaining a constant distance of 20 mm between the air-coupled transducers. The grey values of the images are normalized by the average grey value yielding an amplitude variation image of the tube circumference.

3. Specimen Preparation
This section is concerned with the description of the two types of specimens and their preparation including cyclic loading and the realization of an impact damage.

3.1 Glass FRP and Cyclic Loading
Quadraxial non-crimp fabric (NCF) made of E-Glass fibre rovings from Owens-Corning (OC111A) was infiltrated with resin material from Momentive (resin/hardener combination of RIM135/RIMH137 in a ratio of 100:30) using vacuum assisted resin transfer moulding (VARTM). The NCF consists of eight layers (0°/45°/90°/-45°/45°/90°/-45°/0°). The plies contain various amounts of fibres (49% in 0°, 23% in 45°, 23% in -45° and 5% in 90°). The plate of 2 mm thickness was reinforced at both ends and both sides with tabs of 50 mm width made of FRP and aluminium for force application. Three specimens were cut out of the plate by a diamond blade into dimensions of 250 mm length and 25 mm width. Fatigue damage was induced by cyclic loading using a servo hydraulic testing machine. A ratio between the minimum and the maximum stress of \( R = 0.1 \) and a frequency of \( f = 4 \text{ Hz} \) were employed. The direction of force application (18 kN) was along the 0° layers. The specimens were repetitively taken out of the testing machine for measuring the guided wave velocity along the 0° layers.

3.2 CFRP Tubes and Impact Damage
Two types of tubes (radius: 25 mm, length: 300 mm and wall thickness: 2.5 mm) were made of CFRP. The specimens were manufactured with prepreg technology using unidirectional (UD) fibres (HS150 EE24 REM CARBON UD PREPREG, SEAL S.p.A) and liner fabric (SIGRATEX PREPREG CE 8208-165-45s, SGL CARBON GROUP). The difference between the two specimen types is found in the ply layup: the first set of tubes was manufactured with a layup containing 8 layers of UD fibres in between 4 layers of linen fabric (4x ±45°/8x ±0°/4x ±45°). For the second ply layup, it is only known that it contains less or non 0° layers. Impact damage was induced in the two types of tubes/laminates by five different impact energies (5, 10, 20, 30, and 40 J).

4 Results and Discussion
The results of fatigue monitoring in the glass fibre reinforced (GFRP) specimens and the evaluation of impact damage in the CFRP tubes are presented and discussed in this section.

4.1 Monitoring of Fatigue
The velocity of the guided wave decreases rapidly within the first 200 cycles in the stepwise fatigued GFRP specimens, as illustrated in Fig. 2 for specimen 1. This corresponds to the steep decline in Young’s modulus which was measured by the servo hydraulic testing machine (Fig. 2). The following phase II of composite fatigue is accompanied by moderate stiffness degradation which correlates to the gradual decline in guided wave velocity. The good agreement of guided wave velocity and stiffness degradation is also shown for all specimens (Fig. 3). The decrease in velocity is caused by a change in stiffness due to mechanical induced fatigue damage. This decline in stiffness is mainly due to matrix cracks which were monitored in the transparent material as well (Fig. 4). The matrix cracks observed mainly develop in the ±45° and 90° rovings. In the 0° ply, the fibres carry the force applied and the matrix remains almost undamaged.

4.2 Detection of Impact Damage
The area-scans of the tube surfaces show a strong amplitude variation in the areas of the delamination due to impact. Different sizes of the delamination due to the impact energies of 5 and 20 J are
detectable (Fig. 5 and 6). The $0^\circ$ UD layers in the middle of the first type of laminate induce an elongate delamination. The second stacking sequence (probably without $0^\circ$ UD plies) results in a rounder shape (Fig. 7). Reference measurements using optical lock-in thermography are used to verify the ultrasound result (Fig. 8).

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**Fig. 1.** Setup for single-sided non-contact ultrasound measurement [8].

**Fig. 2.** Guided wave velocity and Young’s modulus over fatigue cycles for specimen 1.

**Fig. 3.** Guided wave velocity over Young’s modulus for all GFRP specimens.

**Fig. 4.** Photograph of matrix cracks induced by cyclic loading in the NCF composite.

**Fig. 5.** Guided wave area scan across impacted tube (5 J low velocity impact), stacking sequence ($4x \pm 45^\circ/8x \pm 0^\circ/4x \pm 45^\circ$).
Fig. 6. Guided wave area scan across impacted tube (20 J low velocity impact), stacking sequence (4x ±45°/8x ±0°/4x ±45°).

Fig. 7. Guided wave area scan across impacted tube (20 J low velocity impact), layup with lower ratio of 0° UD plies.

Fig. 8. Optical lock-in thermography phase image of impacted tubes (5 10 20 30 and 40 J) with the ply layup (4x ±45°/8x 0°/4x ±45°). Tube length 300 mm.

References


