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An experimental study on the effects of matrix cracking to the stiffness of glass/epoxy cross plied laminates

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ABSTRACT

Three independent measurement techniques are applied to characterize glass fiber laminates. The effects of distributed fatigue damage to the stiffness related behavior of cross plied laminates are quantified. Tensile and flexural stiffness reduction is obtained from quasi-static testing. Vibration testing shows the degradation of flexural and in-plane shear stiffnesses. The reduction of the phase velocity of symmetric S_0 mode is observed from the experimental dispersion curves of Lamb waves. However, the mutual agreement of these results is less satisfactory than was earlier seen for virgin laminates. The phenomena causing the discrepancies are proposed and discussed.

1. Introduction

The stiffness of a composite material is determined by its:

- intrinsic properties (stiffness of a virgin material);
- intrinsic and the damage properties (stiffness of a damaged material).

It follows that experimental stiffness measurements can provide information about the elastic constants of the virgin material as well as the stiffness degradation of the damaged material. Various non-destructive monitoring systems are able to detect the occurrence of material damage. Fewer systems, however can quantify stiffness and its reduction. A stiffness based non-destructive evaluation system needs to foresee how damage influences the measured parameters. Some early reviews about non-destructive testing techniques and defects in composites were given in Refs. [1,2]. Current work focuses on a distributed form of damage, a network of matrix cracks from fatigue, as opposed to local single defects. This type of damage typically appears early in the component life, with initially little effect on structural integrity. However, it is a precursor to more severe forms of damage, as the tips of matrix cracks can become the initiation points for delamination and fiber failure.

Stiffness measurements can be based on vibration testing, or ultrasonic Lamb wave velocity measurements, in addition to well-known static test techniques. A thorough review on Lamb wave based damage identification in composites has been compiled in Ref. [3]. The Lamb wave investigations into distributed forms of damage can be divided into two categories: thermal-mechanical aging [4–7], and transverse cracking due to fatigue [8–18]. Summarized reviews about vibration related research can be found in Refs. [19,20]. Some recent research about the vibration testing of virgin plates and its use for elastic constant determination has been published in Refs. [21–24]. The influence of fatigue damage on natural frequencies has been studied in Refs. [25–33]. Although advanced modelling can also employ damping or attenuation, e.g. Refs. [34], these energy dissipation mechanisms can typically be disregarded for thermoset laminates without introducing overly large errors to the identified stiffnesses.

Some open issues were identified from previous scientific work. First, the degradation of E_2 modulus due to transverse cracks is well

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known. However, the amount of degradation and whether a complete restauration of initial modulus should be assumed in compression (as is often done), is not clear. Also noted, in-plane shear stiffness reduction has been reported due to transverse cracking, showing its applicability as a damage indicator. Shih et al. [11] noted that progressive opening of transverse cracks (e.g. from tensile load) caused the guided wave velocity to decrease i.e. there is a difference in wave velocities, depending on whether transverse cracks are open or closed. Papers by Rheinfurth, Paipetis, Toyama et al. [15,17,35] have noted that Lamb waves (both A_0 and S_0) can propagate separately in isolated surface plies (sub-laminates) which are created in delaminated areas. Overall, the effect from fatigue damage to plate wave velocities is not well understood. Further, the ultrasonic Lamb wave studies have historically been more focused on carbon and graphite fiber composites. Studies about glass fiber composites have been published fairly recently [14–18,35]. In many of the Lamb wave studies the velocities measured from waveforms are compared to an initial reference. Traces of Lamb wave dispersion curves, measured on transversely cracked glass-fiber laminates are rarely published. No studies have been found which experimentally characterizes the same glass fiber composite material from three independent measurements (mechanical static, vibration and Lamb wave).

This research summarizes the experimental work from mechanical quasi-static, natural frequency and Lamb wave propagation measurements. The specifics of test specimens and experimental set-ups are discussed in the first half of the paper. In the second half, the experimental results from three independent methods are calculated and presented. Finally, in the discussion, the experimental outcome from three methods is compared and conclusions drawn.

2. Materials and experiments

2.1. Test specimens

All measurements were conducted on glass/epoxy cross plied laminates. The details of specimens and their production are given in Table 1. The VARI (vacuum assisted resin infusion) process produced laminates with 0.8 mm ply thickness on average. Microscopy verified the composite to be of decent quality, without excessive voids. Two types of specimens were manufactured, straight sided coupons and rectangular plates.

The dimensions of the coupons varied slightly — average widths b from 19.05 mm to 24.85 mm (when cutting, focus was put on obtaining parallel sides over equality of widths), and thicknesses h from 4.79 mm to 4.91 mm. The lengths of the specimens were chosen so that the gauge length in tensile testing was always over 80 mm. The span length to height ratios L/h in three-point bending were chosen either 53 or 72, rendering the shear based deflections negligible.

Rectangular plates have the in-plane dimensions of ca. 30×30 cm^2, other specific details are given in the following sections. The principal in-plane directions for plate specimens are denoted by $x-y$, with x pointing in the 0°direction for the plate layup, e.g. for $TR11\_1F$ $[90_2/0_2/90_2]$ in Fig. 1(b).

Two almost identical plate specimens of $[90_2/0_2/90_2]$ layup were produced to investigate the stiffness reduction from fatigue by non-destructive measurements. Plate $TR11\_1F$ is the damaged analogue to $TR11\_1$, a virgin specimen without damage. Homogeneous fatigue damage (Fig. 1(a)) was introduced to plate $TR11\_1F$ by a 1000 kN tensile test machine. Fig. 1(b) shows plate $TR11\_1F$ in the test machine during fatigue loading cycles. It was loaded with 150 cycles of sinusoidal $R = 0.1$, $\sigma_{max} \approx 0.4\sigma_{ult}$ tensile stress in the x-direction. The uncertainty about the fatigue behavior of this specific set-up was the main reason for applying so few cycles. The transverse crack spacing in the outer plies of $TR11\_1F$ was measured 2.2 mm on average, agreeing well with the crack spacing in small coupons of same layup after 10,000 cycles. This indicates that transverse crack saturation had been reached in the plate $TR11\_1F$.

2.2. Testing with uniaxial test machines

2.2.1. Quasi-static testing

Uniaxial tensile and three-point flexural test methods were employed to measure the effective Young's modulus for the coupon specimens. Test machines Zwick/Roell Z250 (with videoXtens optical extensometer) and Zwick/Roell Z2.5 were used for tension and flexure, respectively. The strain rates at any single point on the specimens were estimated below 0.3% min^{-1}, minimizing possible viscoelastic effects. The slack was removed from the system by slight pre-loading. The absolute maximum strains in the specimen were kept below 0.2% (incl. the pre-load) to avoid creating matrix cracks for the virgin specimens. The gauge length in tensile testing was always over 80 mm. The stress-strain curve could be seen as linear and the load-to-extension or load-to-deflection ratio was obtained by linear least-squares fitting. These tests measured the effective i.e. laminate tensile or flexural stiffness, calculated from

Table 1
The production details for glass/epoxy laminates.

Fibers	E-glass fibers (layer weights 1152 g/m^2 and 51.2 g/m^2 in 0° and 90° directions)
Matrix	Epoxy (*Epikote MGS RIMR* 135, *Epikure MGS RIMH* 137)
Production	VARI, post curing following the manufacturer's recommendations (80 °C for 15 h)
Specimen cutting	Diamond saw
Fiber vol. fraction	58% on average (burn-off)
Details	Release fabrics (peel plies) were used on both faces of the plates
	Thickness: 4.86 mm (average over all specimens)
	Density: 1946 kg/m^3 (average over all specimens)
Specimens	4×3 straight sided coupons:
	1*a*, 1*b*, 1*c* $[90_2/0_2/90_2]$
	2*a*, 2*b*, 2*c* $[0_2/90_2/0_2]$
	3*a*, 3*b*, 3*c* $[0/90_4/0]$
	4*a*, 4*b*, 4*c* $[90/0_4/90]$
	Three ca. 30×30 cm^2 plates:
	$TR11\_1$ $[90_2/0_2/90_2]$ (x-dir.)
	$TR11\_1F$ $[90_2/0_2/90_2]$ (x-dir.)
	$TR11\_2$ $[0/90_4/0]$