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IMPROVEMENTS TO ULTRASONIC INSPECTION OF DELAMINATION WITHIN WAVY COMPOSITES

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ABSTRACT

Multiple types of defects, including delamination, waviness and porosity may be produced during the composite manufacturing process and service life, which increase the risk of structural failure and also introduce the challenge for defect detection and characterisation. In this study, delamination within wavy composites was inspected with improved signal-to-noise ratio (SNR) by using the optimised wave mode from simulation results. Wave interaction of longitudinal and shear waves with waviness and delamination was simulated in CIVA software. To validate the simulation results, waviness and delamination were detected with desirable wave mode by using an angle-adjustable wedge to control the incident wave mode. Longitudinal waves were found to be sensitive to out-of-plane waviness and shear wave is suitable for delamination detection within wavy region. Results from both simulation and experiment demonstrated that B-scan images obtained from both longitudinal and shear waves can characterise delamination from waviness.

Keywords: composite, delamination, waviness, ultrasound testing, defect characterisation

NOMENCLATURE

CFRP	carbon fibre reinforced polymer
CT	computed tomography
FBH	flat bottom hole
SDH	side drill hole
SNR	signal-to-noise ratio
UT	ultrasonic testing

1. INTRODUCTION

Carbon fibre reinforced polymer (CFRP) composites are increasingly utilised in high-performance structural applications. Different discontinuities can occur during either the manufacturing processes or the service life of the composite components. Without loss of generality, fibre wrinkling and waviness, porosity and ply misalignment can progress during the fabrication process and have the potential to form delamination, debond, and crack defects [1].

For composite structures, both in-plane and out-of-plane waviness can be produced during the curing progress with temperature gradients. Especially for aerospace composite structures with complex shape (e.g., composite fan blade and aerofoil), fibre wrinkling has a high chance to convert to either in-plane or out-of-plane waviness. During the service life of composite structures, static and dynamic stresses along with impact forces can cause layers to separate and generate a small gap between composite layers (i.e., delamination), which usually reduces the structural strength. The existence of multiple types of defect within composite structures increases the risk of structural failure and also introduces the challenge for defect detection and characterisation.

To maintain the service life of composite structures and reduce the potential failures, non-destructive technologies including eddy current [2], X-ray computed tomography (CT) [3-4] and ultrasonic testing [5-12] are widely used to detect and characterise different defects in composite materials. Eddy current technologies can inspect the near-surface regions of composite structures [2]. However, eddy current methods can only penetrate a shallow depth through the composite materials according to the modulation frequency and the material conductivity. X-ray CT technology has been adopted to inspect and characterise different defects in the composite structures, including honeycomb composites, fibreglass power poles, and carbon foams [3-4]. The low contrast between fibre and resin in the X-ray CT results restricts the sensitivity to misalignment of fibre orientation.

Ultrasound testing (UT) is another prevailing technology for surface-breaking, near-surface and sub-surface defect inspection in the composite structures. Guided waves, including Rayleigh waves and Lamb waves, are suitable for surface breaking/near-surface defects and thin composite inspection, respectively [5-8]. However, high attenuation and dispersion properties introduce challenges for application of guided waves for

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inspection of thicker composites. Reported research has demonstrated the capability of longitudinal and shear waves in the inspection of delamination [11], porosity [8] and fibre orientation (in-plane [10] and out-of-plane waviness [9]) in the composite structures with reliable diagnosis. Basically, wave features like wave attenuation and frequency shift can be used to identify delamination and porosity inside the composites. To evaluate fibre orientation, wave attenuation or phase shift of ultrasound during propagation in the composite must be mapped with position information (B-scan and C-scan). Despite promising potential applications, delamination within wavy composites is seldom reported to be evaluated with high signal-to-noise ratio (SNR). Efficient UT methods are required for detection and characterisation of delamination and waviness in composite structures.

In order to extract wave features for defect characterisation within composite structures, wave interaction with delamination and waviness must be fully understood. When ultrasound waves, both longitudinal and shear, interact with delamination, due to acoustic impedance difference between air within delamination and composite material, ultrasound will be reflected at the interface and sometimes even with mode conversion. From both theoretical derivation and experimental validation [9], longitudinal waves were found to follow the fibre direction and are reflected back by fibre waviness when propagating in the composites while transverse waves can transmit through the composites regardless of waviness with a periodic intensity pattern. Smith [11] conducted analytical modelling to investigate the interaction between ultrasound and ply-drop composite plies. With the optimisation of frequency and bandwidth, the ultrasound instantaneous phase can lock onto the resin-rich layers and provide the out-of-plane layer orientation. In-plane waviness is more challenging to inspect for both pulse-echo and through-transmission methods compared to out-of-plane waviness. Currently, wave attenuation characteristics can be used to qualitatively inspect in-plane waviness. However, quantitative evaluation and location of in-plane waviness with constructive guidelines for ultrasound inspection optimisation has rarely been reported. According to different interaction patterns of longitudinal and shear waves with delamination and waviness, delamination within wavy composite should be defected with improved SNR by using transverse waves.

In this study, delamination within wavy composites was inspected with improved SNR by using the optimised wave mode from simulation results. Wave interaction of longitudinal and shear waves with single type defects (waviness or delamination) and delamination within wavy composite was simulated in CIVA software. To validate the simulation results, waviness and delamination (side-drilled holes, SDHs and flat-bottomed holes, FBHs) were detected with desirable wave mode, i.e., either longitudinal wave or shear wave, by using an angle-adjustable wedge to control the incident wave mode. SNR from both simulation and experiment is compared to verify the feasibility of the proposed method in the defect inspection and characterisation in the composite structures.

2. SIMULATIONS AND EXPERIMENTS

As depicted in Figure 1, there exist thin resin rich layers between prepreg layers, which cause ply reflection when ultrasound propagates in composites. The multiple reflections, which become more intensive when in-plane and out-of-plane waviness occurs, introduce difficulties in signal interpretation for composite inspection and reduce SNR for defect identification.

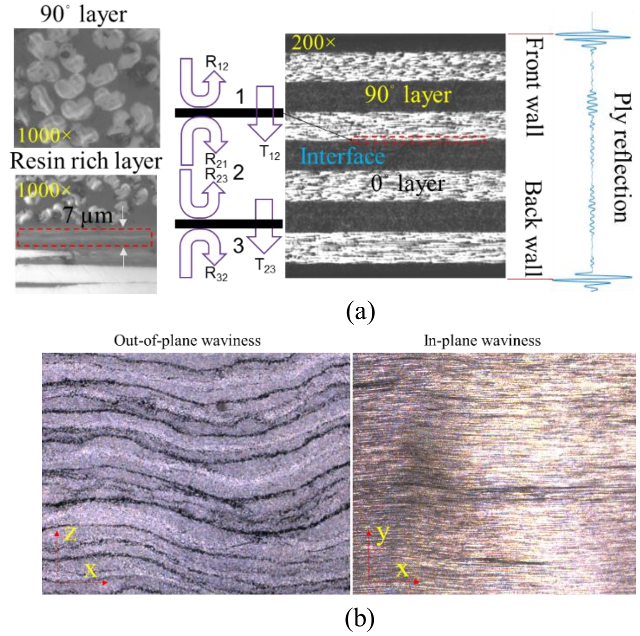


FIGURE 1: (A)WAVE PROPAGATION IN COMPOSITES AND (B) WAVINESS AND DEAMINATION IN COMPOSITE OBSERVED FROM MICROSCOPE

In this section, wave interaction of longitudinal and shear waves with delamination and waviness is to be investigated both numerically and experimentally.

2.1 Simulation of wave interaction with delamination and waviness

The numerical model of wave interaction with delamination within waviness region is shown in Figure 2.

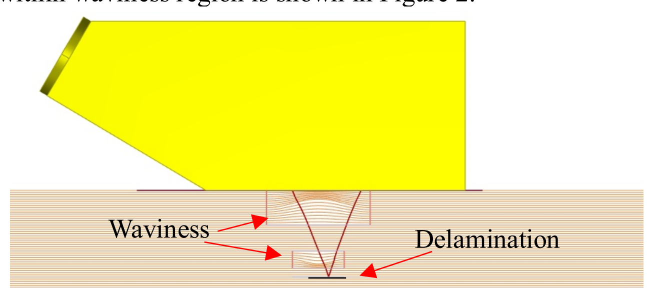


FIGURE 2: NUMERICAL MODEL FOR WAVE INTERACTION WITH DELAMINATION WITHIN WAVY COMPOSITE

The geometry of the model is 100 mm × 100 mm × 6 mm with a layout of [-45 0 45 90]$_{6s}$. 7 μm resin layers were added between composite layers. Two waviness regions within area of 2 mm × 6 mm and 1 mm × 3 mm and delamination with a size of 1 mm

× 1 mm × 1 mm were simulated. Refraction angles of both longitudinal and shear waves were adjusted to achieve the optimised inspection results.

2.2 Experimental inspection and characterisation of delamination and waviness

The experimental set-up for delamination inspection within wavy composite region is shown in Figure 3. Wave controller Peak LT2 was used to generate and receive ultrasound. A 20 MHz probe with an angle-adjustable wedge was used to inspect the delamination within composites with different shapes.

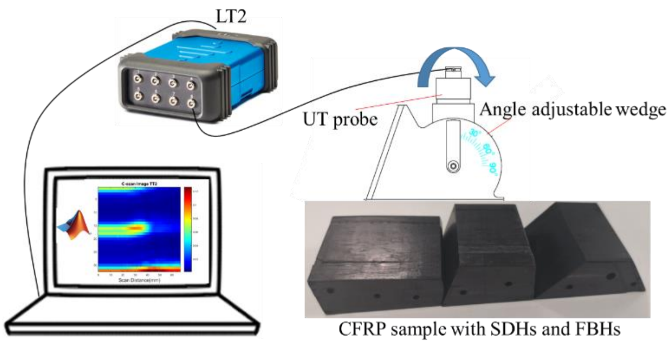
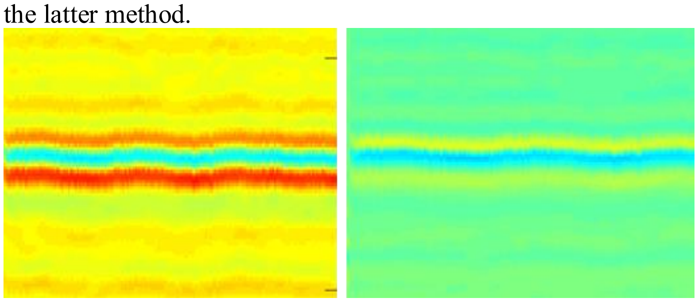


FIGURE 3: EXPERIMENTAL SET-UP FOR DEFECT DETECTION IN COMPOSITES

3. RESULTS AND DISCUSSION

Longitudinal and shear waves show similar sensitivity to delamination. Longitudinal waves are sensitive to out-of-plane waviness and shear waves can propagate through out-of-plane wavy regions without significant energy loss and propagation angle change. B-scan images of one sample obtained from longitudinal wave and shear wave are shown in Figure 4. For the former method, indications of both delamination and waviness can be observed while only delamination is clearly present for the latter method.



(a) (b)

FIGURE 4: B-SCAN IMAGE OF DELAMINATION WITHIN WAVY COMPOSITE FROM (A)LONGITUDINAL WAVE AND (B) SHEAR WAVE

4. CONCLUSION

In this study, delamination within wavy composites was inspected with improved SNR according to different interaction of longitudinal and shear waves with delamination and waviness. Experimental results reached good agreement with numerical simulation. Results demonstrated that longitudinal and shear waves show similar sensitivity to delamination. Longitudinal waves are sensitive to out-of-plane waviness and shear waves can propagate through out-of-plane wavy region without significant energy loss and propagation angle change. Delamination within wavy composites can be inspected with improved SNR by using shear wave. B-scan images obtained from both longitudinal and shear waves can characterise delamination from waviness.

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