Inspection of Manufacturing Defects in Fiber Reinforced Composite Laminates using Ultrasonic Phased Array Probe

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Abstract

Ultrasonic phased array technology is a useful tool for non-destructive testing in various industries for inspection of composite parts during maintenance and manufacturing. In this study, ultrasonic C-scan technique is used to detect various artificial defects with a 5MHz phased array wheel probe in laminated composite plates.The artificial defects with varying shapes and sizes made of polymer films were embedded in the testing plates at different layers and positions. Both unidirectional glass fiber reinforced epoxy polymer (GFRP) and carbon fiber reinforced epoxy polymer (CFRP) composite laminates were examined using portable Doppler PA instrument PHASCAN®. Special tuning and optimization techniques including different element combination and focus settings and distance amplitude correction (DAC) were used to reduce signal noise levels and to achieve better image resolution. The C-scan measurementsarein good agreement with the actual sizeand position of defects: quantifying the size and location of defects. In addition, the attenuation factors in both materials were measured. It was found that the noise to signal ratio in CFRP laminates is much lower than GFRP laminates, which resulted in better C-scan image.

Keywords: phased-array scanning, composite laminates, defects, wrinkles

1. Introduction

There is an increased usage of fiber reinforced composite laminates, especially in aerospace, wind energy industries. As these structures such as fuselage, aircraft wings, wind turbine blades, become larger in size, there is a greater demand for non-destructive evaluation of defects both while manufacturing stage, maintenance, repair and overhaul (MRO) operations. Composite materials are inherently anisotropic and non-homogeneous in nature. Techniques based on thermography, shearography, ultrasonic testing (UT), acoustic emission (AE) testing etc. have been previously employed for the NDE of composites. Ultrasonic testing is routinely used for the quality assurance of composite laminates [1-5].Phased array (PA) is an advanced method for ultrasonic testing (UT) that has applications in industrial non-destructive testing [6-7]. A single element generates and receives sound waves at certain frequency whereas inPA each element can be pulsed differently. The advantage over conventional UT is that it is suitable for complex geometries in defect detection and speed of testing. Focal law establishes specific delay times to generate different beam shapes steer beam angle and adjust focal distance. In this paper, ultrasonic phased array NDT by wheel probewas performed on a group of artificial defect polymer matrix composite laminate samples to analyze them and improve the detection by different techniques.In addition,attenuation was measured and compared for glass fiber reinforced epoxy matrix (GFRP) and carbon fiber reinforced epoxy matrix (CFRP) samples using different manufacturing process.

2. Experimental setup

In this study, a portable Doppler PA instrument PHASCAN was used with a water-filledwheel probe (Fig. 1). The probe has 5MHz frequency 64 elements array with an aperture size of 38.4 mm, pitch of 0.6 mm and an encoder to synchronize the data acquisition with probe movement. The scanning mode used was linear straight scan.CFRP and GFRP laminates embedded with artificial defects in the form of delaminations, resin-rich zones, wrinkles etc were examined in this study. The detailed characteristics of these artificial defects are as follows and are listed in Table 1:

GFRP

- GD1, GD2 and GD3: rectangular shape delamination($60mm \times 40mm$), between layers 2/3,4/5,6/7 respectively
- GD4: A thin strip of delamination ($5mm \times 30mm$)
- GD5: Square shape delamination ($15mm \times 15mm$)
- GD6: Void($35mm \times 35mm$), between layers 2/3

CFRP

- CD1: rectangular shape delamination(width=$50mm$)

Fig.1. Experimental setup for Doppler phased array UT testing

In addition, the attenuation of CFRP and GFRP laminates manufactured from different manufacturing processes were measured. Defects introduced during the manufacturing, including poor resin area and wrinkle defects, were also examined. The wave velocities used for CFRP and GFRP were 2738m/s and 2518m/s respectively.

3. Inspection of artificial defects

The GFRP laminate with defects as shown in Fig. 2 was taken for testing and results of defects were measured and compared with the actual size of the defects. Appropriate software tuning procedures and examination techniques were studied to optimize the scanning results. As a result, an aperture of six elements with sizing curve technique was used for the scanning. The results obtained for various defects in GFRP laminates are as follows:

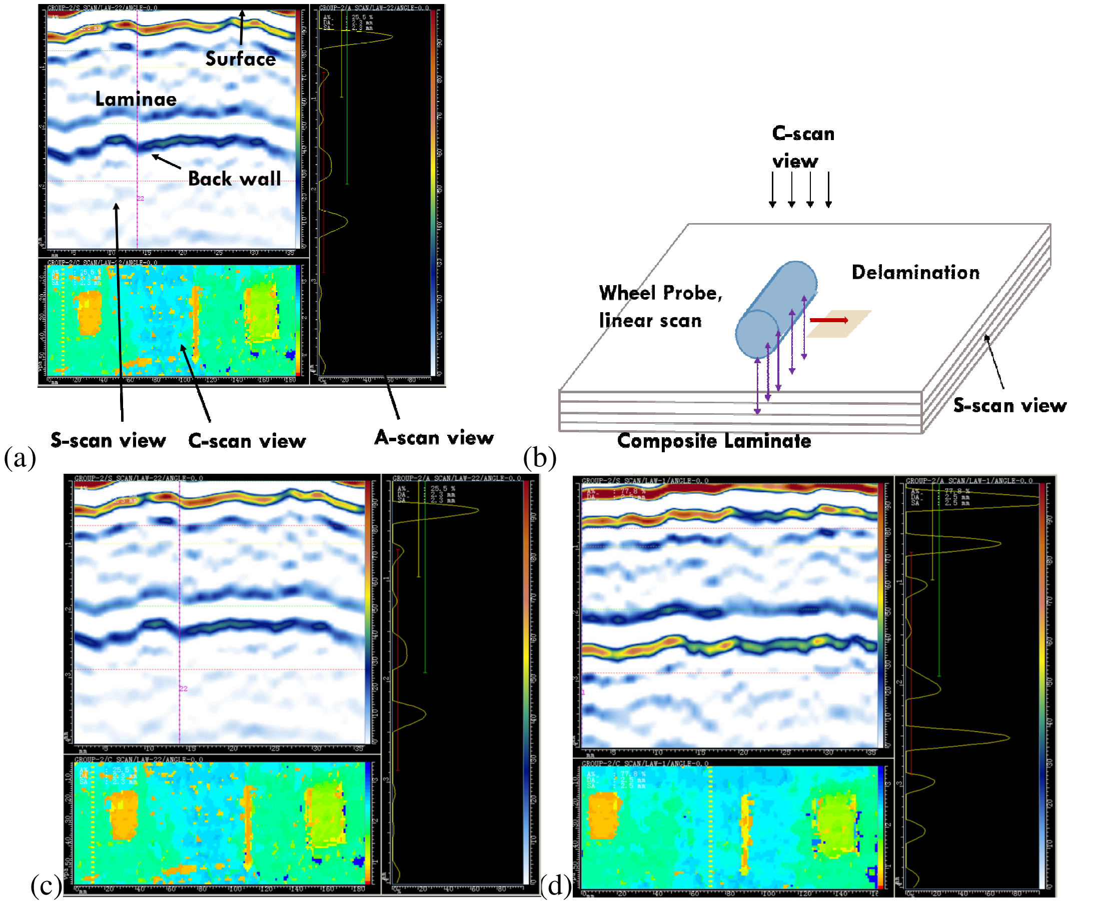


Fig. 2 (a)A,B,C scan view of a GFRP Plate;(b)Schematic Diagram of a UT phased array scaning (c)Unoptimized scanning results(d) Optimized scanning results using six element aperture

The experimental values for the defects are as follows:

Table 1: Testing results for GFRP and CFRP laminates **GFRP Laminate**

Defect	Actual Size	Experimental Size
GD1	60mm ∗ 40mm	Width :66.1mm Thickness :0.8mm
GD2	60mm ∗ 40mm	Width :63.2mm Thickness :1.1mm
GD 3	60mm ∗ 40mm	Width :62.1mm Thickness :2.14mm
GD 4	5mm ∗ 30mm	4mm ∗ 26mm
GD 5	15mm ∗ 15mm	13mm ∗ 16mm
GD 6	35mm ∗ 35mm	30mm ∗ 33mm

CFRP Laminate		
Defect	**Actual Size**	**Experimental Size**
CD1	Width=50mm	Width=50.3mm

4. Attenuation measurement

Attenuation is the decay rate of the wave as it travels through a material. The porosity of composite material has large influence on the attenuation during ultrasonic testing, which can be also related with the material properties[8]. The total attenuation (A)in the specimen can be expressed as,

$$A = 20\log\left(\frac{P_0}{P}\right) \tag{1}$$

whereP_0 and P are the amplitudes of the first signal from the surface and the back wall signal. The total attenuation is comprised with three components, namely front surface losses (A_f), back surface losses (A_b) and the transmission losses (A_t)[9]. The three components are calculated as,

$$A_f = 20\log\left(\frac{Z_w+Z_c}{2Z_c}\right) \tag{2}$$

$$A_f = 20\log\left(\frac{Z_w+Z_c}{2Z_c}\right) \tag{3}$$

$$A_t = \alpha(2t) \tag{4}$$

where Z_w, Z_c, α and t are acoustic impedance of water,acousticimpedance of composite, attenuation coefficient and specimen thickness respectively. The acoustic impedance of GFRP and CFRP are estimated using the following formula,

$$Z_c = \rho v_c = \sqrt{E_{11}\rho} \tag{5}$$

where ρ, v_c, E_{11} are the density, sound velocity and Young's modulus of matrix.Table 2provides the relative properties of CFRP and GFRP laminates:

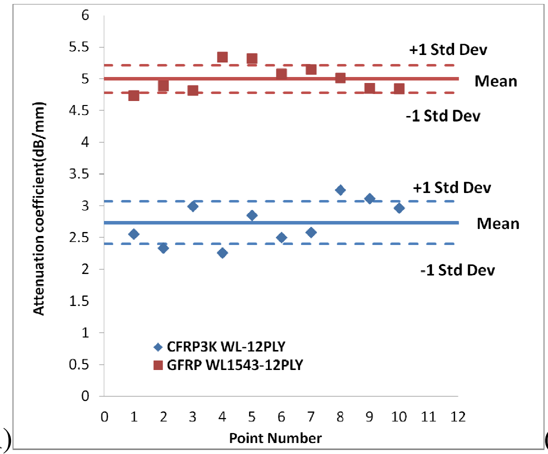
Table 2:Relative Properties of CFRP,GFRP and Water

Material	Velocity(m/sec)	Density(kg/m^3)	Acoustic impedance(10^3Kg/m^{2}s)
CFRP	2738	1600	4381.7
GFRP	2513	1900	4774.9
Water	1483	1000	1483

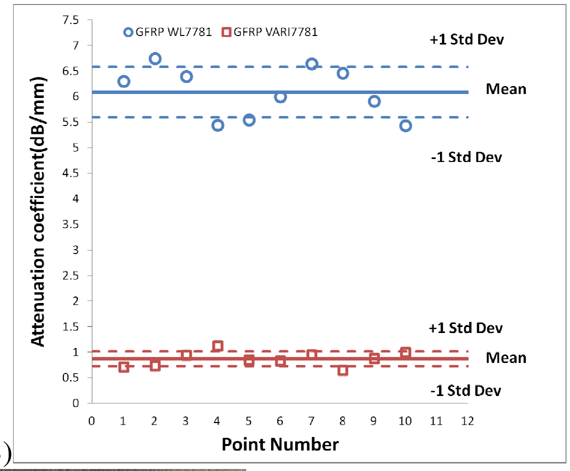
The above formulae were used on the following samples and attenuation coefficient was measured for the following laminates and compared:

a) GFRP WL1543-12Ply versus CFRP3K WL-12Ply
b) GFRP WL 7781 versus GFRP VARI7781

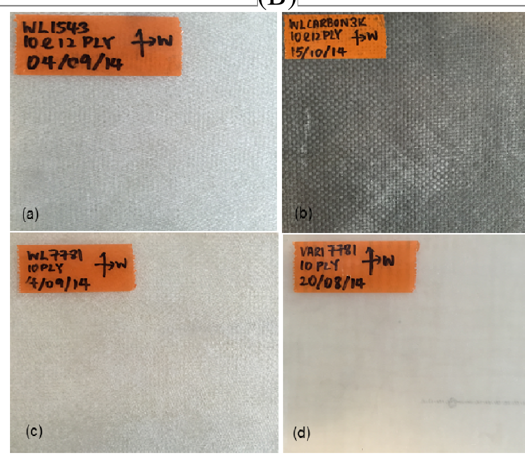
The attenuation coefficient at various locations was plotted and compared as shown in Figure 3. It shows that the CFRP laminates have a higher attenuation than the GFRP laminates and also the laminates manufactured under different processes have significant impact on the attenuation.



(A)



(B)



(C)

Fig. 3(A)Attenuation Coefficient b/w GFRP WL1543-12Ply vs CFRP3K WL-12Ply (B)Attenuation Coefficient b/w GFRP WL 7781 vs GFRP VARI7781 (C)Laminates used for Testing .

Inspection of Manufacturing Defects:

Ultrasonic testing was also measured on a few laminates with defects which included improper resin, wrinkles etc. and their corresponding C-scans are measured are as show in figure 4.

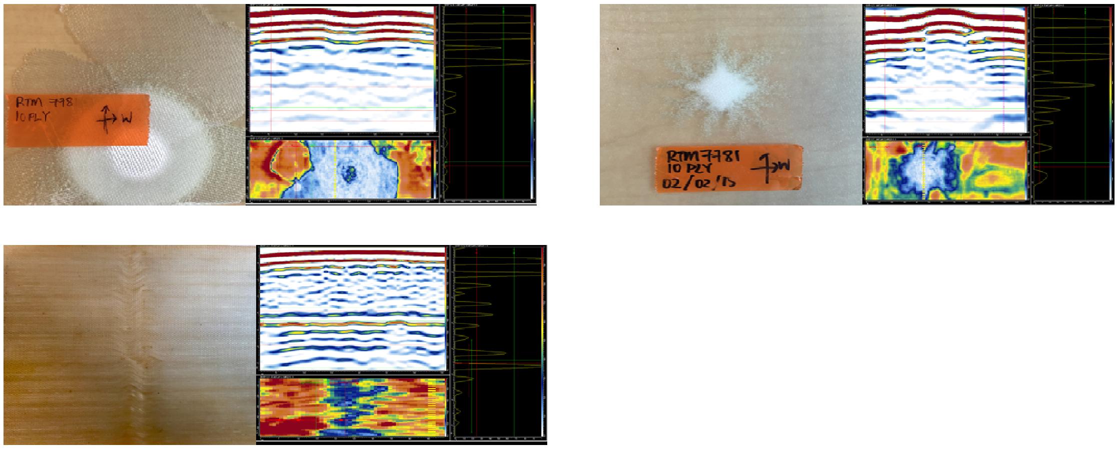


Fig.4.Inspection of Manufacturing defects and corresponding C-scans.

5. Conclusion

Different composite laminates with pre-incorporated defects were examined using ultrasonic phased array technique and have lead to increased accuracy of the defects, speed of testing using different techniques like the six element and sizing curves. The attenuation measured between CFRP and GFRP laminates show that CFRP have higher attenuation than the corresponding GFRP laminates. The experiment also shows that laminates manufactured under different processes have significant impact on attenuation measured which can be related to porosity and mechanical properties of the laminates. An estimation on area impacted by impact testing on one of the composites can be done and simulation can be created using FE models and the effects can be investigated in the future.

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