ULTRASOUND DETECTION OF ANOMALIES IN MULTI-LAYERED FIBRE-REINFORCED POLYMERS

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ABSTRACT

This paper investigates the application of UT to detect anomalies within multi-layered systems consisting of fibre-reinforced polymer. The study shows the combination of UT variables that give the best accuracy in detecting the size of the anomalies and with minimal noise in its signal, within 2-layered and 3-layered polymer composite panels with fibre-reinforcement layers.

1 INTRODUCTION

Ultrasonic testing (UT) is a non-destructive test often used on composite components or structures to detect defects or anomalies [1-2]. There are a variety of these anomalies that can be present in composite materials, including delamination, voids, cracks and inclusions [3].

However, the main challenge for UT of multi-layered, fibre-reinforced components are the high attenuation and scattering of ultrasonic waves, which cause difficulties in accurately identifying and measuring anomalies within the material [4, 5]. In order to circumvent this, lower frequencies may be used, but at the expense of penetration depth of ultrasound waves. This then poses an issue for detecting anomalies deep within thicker components.

This paper investigates the application of UT to detect anomalies within 2-layered and 3-layered specimens. The 2-layered specimen consists of a top layer of polyethylene and a layer of fibre-reinforced polyethylene underneath while the 3-layered specimen is a middle layer of fibre-reinforced polyethylene sandwiched between a layer of polyethylene at the top and bottom. The study covers the UT method and design of experiment (DOE) analysis to optimise the settings in order to accurately detect anomalies in both 2-layered and 3-layered specimens.

A phased-array UT system is used to scan the panels, and the study covers a transducer frequency range of $2f_o$ to $4.5f_o$ MHz and E to $2E$ number of firing elements, which represents the aperture size. The noise in the detected ultrasound signals is also characterised by a noise factor. The study shows the combination of UT variables that give the best accuracy in detecting the size of the anomalies and with minimal noise in its signal. It also demonstrates how defects in the different layers of a multi-layered component can be accurately measured.

2 EXPERIMENT

2.1 Sample preparation

2.1.1 2-layered specimen

The 2-layered composite panels are made from 0.25 mm thick unidirectional glass fibre reinforced polyethylene sheets (70 weight % fibre). Each sheet is cut into 200 mm × 150 mm dimensions with 0° and 90° fibres as shown in Figure 1. The layup, i.e. $[0°/90°]_{10}$ is placed in a 2.5 mm thick stainless steel mould and hot-pressed at a temperature of 210°C and pressure of 7 MPa for 10 minutes and cooled down straight after for another 10 minutes.

In order to simulate anomalies in the panels, 0.5 mm thick silicon tape is embedded between the fifth and sixth layers of the panels. The panels made are shown in Figure 2, for those with and without the embedded anomalies.

An additional polyethylene panel of 2.5 mm thickness is adhered to the top of the hot-pressed panel such that the combined panel is a top layer of pure polyethylene followed by a bottom layer of glass fibre reinforced polyethylene. Figure 3 shows a photo and illustration of this.

Mechanical micrometre measurements give an average thickness of 5.38 mm for each combined panel made. Table 1 shows the average caliper measurements for the anomalies.

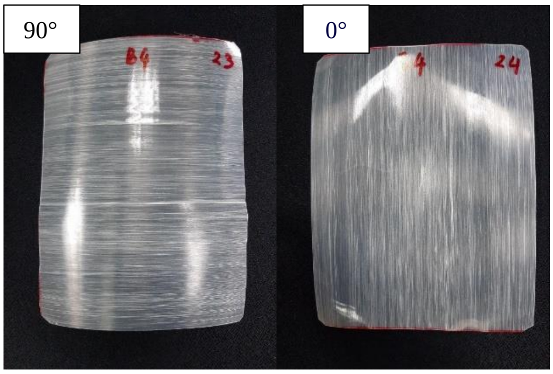


Fig. 1. Unidirectional glass fibre reinforced polyethylene sheets (90° and 0° orientations)

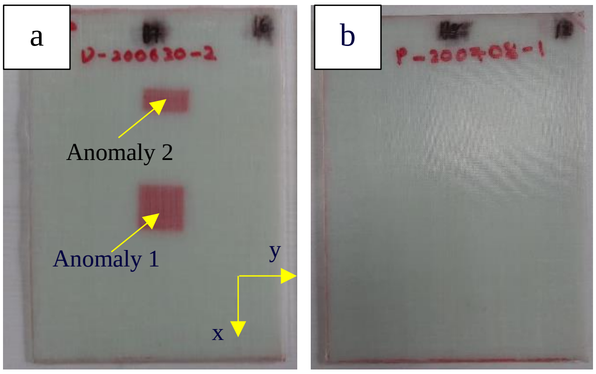


Fig. 2. Hot-pressed composite panels (a) with embedded “anomalies”; (b) without anomalies

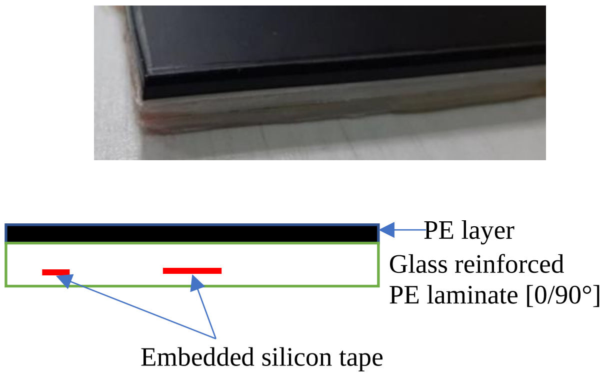


Fig. 3. Photo and illustration of the layers of material of the panels

Table 1. Average mechanical measurements of the combined panel

	Mechanical Measurements, mm
Anomaly depth (*z*)	4.09
Anomaly 1 width (*x*)	26.46
Anomaly 1 height (*y*)	26.88
Anomaly 2 width (*x*2)	14.00
Anomaly 2 height (*y*2)	26.00

2.1.2 3-layered specimen

The 3-layered specimen is made from a component with a middle layer of fibre-reinforced polyethylene sandwiched between a layer of polyethylene at the top and bottom (Figure 4). The layers are all thermally fused together. Features are machined on the external and internal surfaces of the component to represent the anomalies. Another set of component with delamination in the fibre-reinforced layer is also prepared.

The total thickness of the specimen is approximately 32 mm, with dimensions of the machined features in Table 2. The specimen with delamination has the defect at a depth of 6.12 mm within the reinforcement layer as shown in Figure 4b.

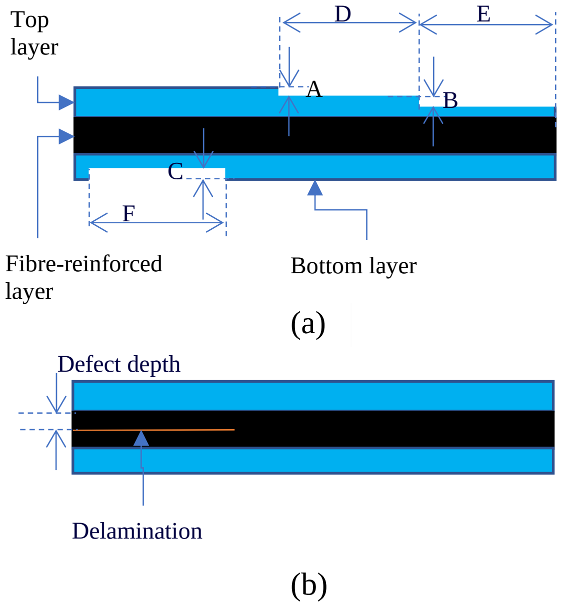


Fig. 4. 3-layered specimen (a) with machined features on internal and external surfaces; (b) with delamination within fibre-reinforced layer

Table 2. Dimensions of machined features

	Mechanical Measurements, mm
A	3
B	3
C	3
D	30
E	30
F	30
Defect depth	6.12

2.2 Main variables

A design of experiment (DOE) is conducted with two main variables: the ultrasound frequency and the number of scanning elements. The ultrasound frequency is considered between $2f_o$ to $4.5f_o$ MHz, which is a typical range used for composites. Meanwhile, the number of scanning elements is set between E to $2E$ elements. This is a balance between having a high enough resolution in the phase array scan and requiring large number of elements to scan a full-sized component.

2.3 Responses

The DOE analysis covers multiple responses to the two main variables mentioned above, focusing on the dimensional accuracy of the embedded defects in the panels. There are four responses, namely the differences between ultrasound measurements (x_u, y_u, z_u) and mechanical measurements using a caliper (x_c, y_c, z_c) for the x, y and z dimensions of the anomalies – denoted as Δx, Δy, Δz – and the noise factor, K.

Equations 1-3 define the first three responses.

$$\Delta x = \left| x_u - x_c \right| . \qquad (1)$$

$$\Delta y = \left| y_u - y_c \right| . \qquad (2)$$

$$\Delta z = \left| z_u - z_c \right| . \qquad (3)$$

The noise factor, K, is a measure of how much noise in the ultrasound intensities that needs to be filtered out in order to produce a good resolution of the anomalies being detected. The ultrasound intensities within the “good region” of the specimen is used as a reference for mean, μ and variance, σ^2 in peak intensities. The factor K is introduced as a multiplier of the variance as per Equation 4, indicating higher noise when a higher value is required.

$$\mu \pm K\sigma^2 . \qquad (4)$$

2.4 Ultrasound methods

Ultrasound measurements of the panels are conducted using the MX2 OmniScan acquisition unit from Olympus. The experimental setup is depicted in Figure 5 whereby the panels are immersed in water and scanned with a phased-array transducer attached to an XY-glider system that records the x and y locations of the transducer during the scan. The general settings of the scan include a focus depth on the front-wall of the panel, velocity of 2445 m/s and gain of 11 dB such that the maximum peaks remain below 150% amplitude. A-, B-, C-, and D-scans are obtained using this method.

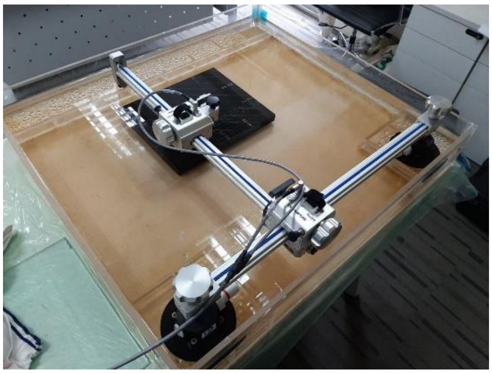


Fig. 5. Experimental setup for ultrasonic measurements of panels

3 RESULTS AND DISCUSSION

3.1 Noise factor *K*

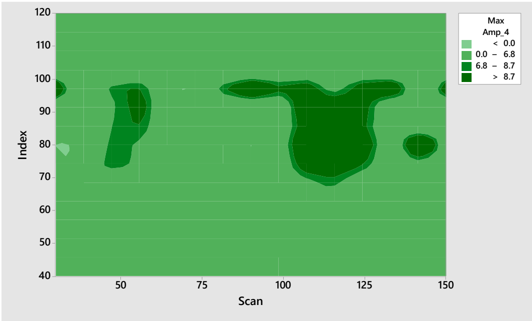
The C-scan of the panel has a lot of noise, which can be filtered out using the reference "good region" of the panel giving an image as shown in Figure 6a. However, the edges of the anomalies are still not well-defined. By introducing the noise factor, K, the signal is further enhanced, as per Figure 6b. In addition to the 2 embedded anomalies, some voids are also present in the panels from the manufacturing process.

3.2 DOE Responses

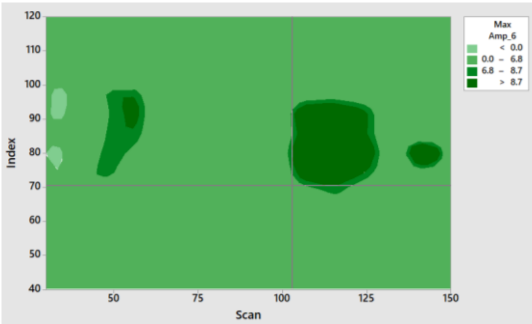
The responses of the DOE for different combinations of frequency and number of elements are listed in Table 3. Analysis of the data to minimise all responses shows that both frequency and elements are main factors that influence the noise and accuracy of dimensions. As shown in Figure 7, frequency of $2f_o$ MHz and $2E$ number of elements give the optimum responses. Frequency has a high effect on all four responses – a lower frequency minimises all the responses. Meanwhile, the number of elements has more significant effect on the noise rather than the dimensions – showing small effects on the dimensions, Δx, Δy, Δz, but a large effect on the noise.

Furthermore, a comparison of the effects of frequency and number of elements on the noise is represented by the Pareto of standardised effects in Figure 8, where both factors are statistically significant at the 0.05 level for response K. Even though both factors affect K significantly, frequency has a higher effect on the noise compared to number of elements.

In terms of dimensional accuracy, Table 4 shows a comparison between mechanical and UT measurements of two anomalies within a panel. The UT measurements are those of the optimum setting of $2f_o$ MHz and $2E$ elements. The accuracy of UT is more than 94% for x, y and z.



(a)



(b)

Fig. 6. Filtering of noise from the C-scan of the panels (a) using reference "good region" and (b) using an additional K factor

Table 3. Responses of the DOE

Frequency	Elements	K	Δx	Δy	Δz
$2f_o$	E	4.33	0.22	0.02	0.00
$4.5f_o$	E	6.78	0.42	0.22	0.11
$2f_o$	$2E$	2.50	0.21	0.18	0.03
$4.5f_o$	$2E$	5.95	0.26	0.22	0.18
$2f_o$	E	4.33	0.08	0.11	0.00
$4.5f_o$	E	6.78	0.20	0.12	0.11
$2f_o$	$2E$	2.50	0.03	0.00	0.03
$4.5f_o$	$2E$	5.95	0.16	0.14	0.11

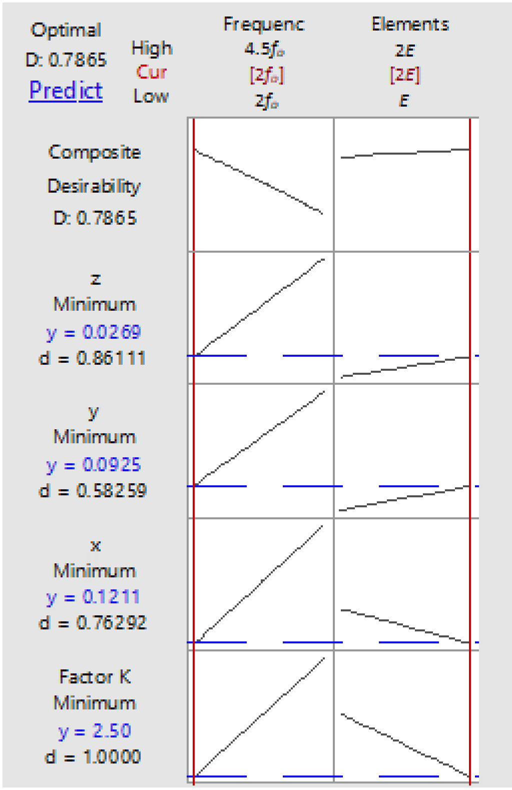


Fig. 7. DOE analysis of responses to factors

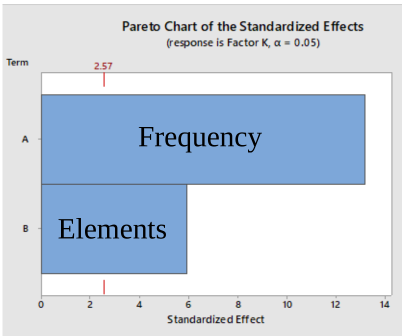


Fig. 8. Pareto of standardised effects for response of K to frequency and number of elements

Table 4. Comparison between dimensions from mechanical and UT measurements

	Mechanical Measurement, mm	UT scan, mm	**% Accuracy**
Anomaly depth (z)	4.09	4.20	**97.3**
Anomaly 1 width (x)	26.46	26.33	**99.5**
Anomaly 1 height (y)	26.88	25.50	**94.9**

Anomaly 2 width (x)	14.00	14.83	**94.1**
Anomaly 2 height (y)	26.00	25.43	**97.8**

3.3 3-layered specimen

UT B-scan on the 3-layered specimen using the optimum setting of 2f_o MHz and 2E elements, is shown in Figure 9, clearly defining the inner, outer and reinforcement layers. The measured thicknesses (P,Q,R,S) of the panel at different regions are used to obtain the depth of machined steps (A,B,C). This is shown in Figure 10 in comparison to the mechanical measurements using caliper, giving 93.6% to 99.5% accuracy.

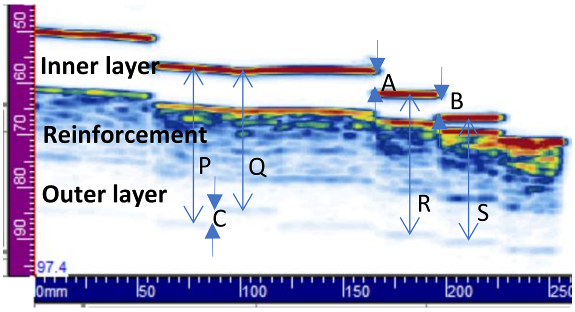


Fig. 9. B-scan image of 3-layered specimen

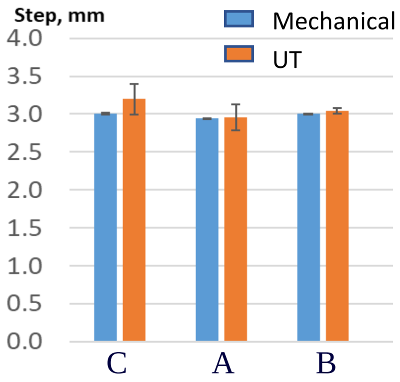


Fig. 10. Comparison of step-depth measured using mechanical caliper and UT scan

The width of the steps (D, E, F in Figure 4a) are likewise compared with mechanical caliper measurements in Figure 11. The accuracy of UT measurement is >95%.

The delamination in the reinforced layer is also detected as shown in Figure 12. Its depth within the reinforced layer is measured in comparison with mechanical measurement. Because the delamination extends to the edge of the specimen, the depth is able to be measured using a ruler and caliper. Using UT it is approximately 6.18 mm, giving 98.97% accuracy.

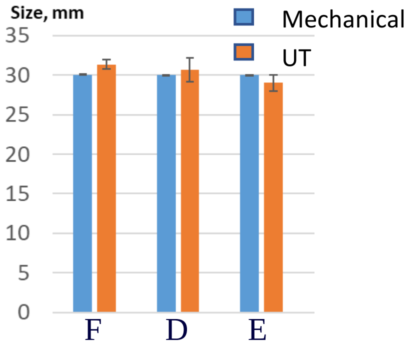


Fig. 11. Comparison of size or width of steps measured using mechanical caliper and UT scan

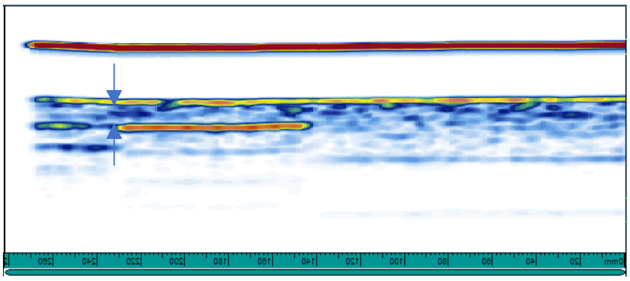


Fig. 12. B-scan of 3-layered specimen with reinforcement delamination defect

4 CONCLUSIONS

This study has shown the application of UT to detect embedded anomalies within 2-layered and 3-layered polymer composite panels with fibre-reinforcement layers. In addition, it has been demonstrated that the noise factor, K can be effectively used to represent the "noisiness" of the ultrasound signals.

DOE analysis was used to identify the frequency and number of elements as main factors that influence the signal noise and dimensional accuracy of the anomalies. Frequency is the primary factor that significantly affects all responses, while the number of elements only significantly affects the signal noise.

The optimised factors give more than an average 94% dimensional accuracy.

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