

Detection, characterization and simulation of delamination defects in composite laminates by ultrasound

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Abstract

This article presents a simulation of the acoustic interference field detected by a delay line after the interaction of an acoustic field with a multilayer carbon fiber composite material, utilizing the ray approach. The simulation is performed on two composite materials: one intact and the other with a delamination defect. Experimental measurements are conducted on carbon fiber composite plates, both with and without pre-introduced delamination defects, without prior knowledge of their thickness. Each ply's thickness is 0.125 mm. A focusing immersion transducer operating at a frequency of 10 MHz is used. The simulation results closely match the experimental data. The model is further applied to determine the thickness of the induced delamination, which is found to be 0.2 mm, located between the second and third layers.

Keywords: non-destructive testing, carbon fiber composite materials, delamination, focusing transducer.

Introduction

Carbon fibre composite materials are important in manufacturing industries because they are lightweight and have excellent mechanical and chemical resistance, unlike conventional materials. In various high-tech industrial sectors, such as aerospace and automobiles, their usage has become widespread. They have the advantage of increasing the lifespan of some equipment due to their chemical properties. Defects can occur and be present in composite materials when subjected to mechanical, thermal, and impact stresses.

For several decades, specialists have sought to develop a non-destructive means for controlling interface defects in a laminated structure in order to guarantee the quality of adhesion both in production and in maintenance [1, 2]. Nowadays, composite materials are experiencing a boom in non-destructive testing (NDT). Much experimental work has been dedicated to non-destructive testing (NDT) of the state of health of these materials (defects, changes in local properties, etc.). Among the existing techniques in non-destructive testing, we can cite, among others, ultrasonic methods [3–5], acoustic emission [6, 7], echography [8], radiography testing [9, 10], and thermography [11, 12].

Several studies have been conducted on the use of ultrasound in the characterization and control of materials. This work led, following the discovery of piezoelectric materials, to the manufacture of the acoustic microscope. Using the acoustic microscope, we can have signals that give us a lot of information about the materials studied, either in imaging or quantitative evaluation of several characteristics such as elastic constants [13,14], the thicknesses of the layers of covering materials and coatings defaults [15, 16], and internal cracks [17].

The focus of this study is to assess the acoustic properties of artificial defects, such as delamination, found in laminated composite plates. To accomplish this, we utilized the experimental technique of ultrasonic signal analysis to obtain data on the thickness of delamination. A calculation program was formulated and implemented to determine the thickness of the delamination.

The perspective of this work is to repeat the experiment for different delamination between different plies with different orientations. Once the model is done, it will be used to design an interface to the US scanner to characterize any delamination defects in carbon fiber composites.

SIMULATION MODEL

In our theoretical study, we have created a simulation of an experimental device, which consists of transducer-composite materials, as shown in figure 1. The transducer in the device has a delay line. The

piezoelectric plane material has been divided into small, equal elements. Each element produces the ultrasonic transmitter note at the same frequency and with no phase shift between them. The goal is to calculate the field received by the piezoelectric material, which is noted as u_0^- .

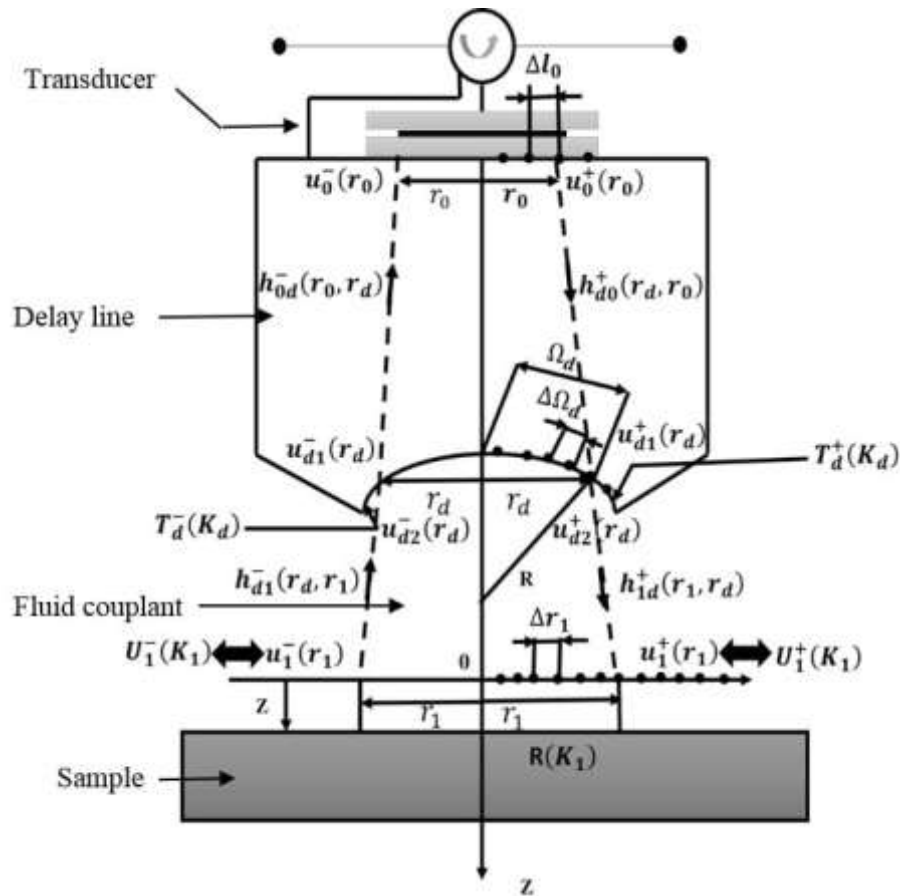


Fig. 1. Geometry for calculating the US response field [18].

The acoustic field u_0^+ emitted by the transducer is transformed into u_{d1}^+ by the delay line. u_{d1}^+ then passes through the dioptr and becomes u_{d2}^+ . Then, u_{d2}^+ turns into u_1^+ after the path of the fluid couplant. The acoustic field u_1^- is obtained after reflection on the sample. u_1^- turns then into u_{d2}^- after it travels through the couplant. By passing through the dioptr, u_{d2}^- turns into u_{d1}^- . Finally, u_{d1}^- is transformed into u_0^- by the delay line.

This methodology for determining the acoustic field u_0^- received by the transducer from the initially emitted u_0^+ acoustic field is summarized in Table 1, which specifies the mathematical transformations required for transitioning from one medium to another.

Table 1. Steps for calculating the received acoustic field.

u_0^- : Field received by the transducer in a negative direction.

u_0^+ : Field emitted by the transducer in a positive direction.

	$u_0^+ \xrightarrow{\text{delay line}} u_{d1}^+$
u_{d1}^+	Field received by the lens (dioptr) in the positive direction
	$u_{d1}^+ \xrightarrow{T^+} u_{d2}^+$
u_{d2}^+	Field emitted by the dioptr in the positive direction
	$u_{d2}^+ \xrightarrow{h_{1d}^+} u_1^+$
u_1^+	Field received by the sample in a positive direction
	$u_1^+ \xrightarrow{\text{FFT}} U_1^+$
FFT	The Fast Fourier Transform
	$U_1^+ \xrightarrow{R} U_1^-$
R	Reflection coefficient
	$U_1^- \xrightarrow{\text{IFFT}} u_1^-$

IFFT	The inverse fast Fourier transform
$u_1^- \xrightarrow{h_{1d}^-} u_{d2}^-$	
u_{d2}^-	Field received by the dioptre in the negative direction
$u_{d2}^- \xrightarrow{T^-} u_{d1}^-$	
u_{d1}^-	Field emitted by the dioptre in the negative direction
$u_{d1}^- \xrightarrow{\text{delay line}} u_0^-$	
U^+, U^-	Angular spectra of the fields.
T^+, T^-	Transmission coefficient at the diopter interface in the forward and reverse directions.
h_{1d}^+, h_{d1}^-	Matrix consisting of the values of the spatial impulse response of the field, at point r_1 of the focal plane for an emission coming from point r_d on the exterior surface of the diopter, and vice versa (figure 2).

Knowing that equation (1):

$$u_0^-(K_1^P) = \text{IFFT}\{U_0^-(K_1^P)\} \quad (1)$$

With

$$U_0^-(K_1^P) = \text{FFT}(K_1^P, r_1^n) \times [h_{01}^-(r_0^m, r_1^n)]^T \times u_0^+(r_0^m) \quad (2)$$

The values of h between two points separated by r are calculated by the following expression (figure 2):

$$h = \sqrt{\frac{jk}{2\pi}} \frac{\exp(-jkr)}{\sqrt{r}} \left(\frac{1+\cos\alpha}{2} \right) \quad (3)$$

With

$$r = \sqrt{(r_1 - r_0)^2 + (z_1 - z_0)^2} \quad (4)$$

and

$$\cos \alpha = \frac{r_0(r_0 - r_1) + (z_0 - z_1)(z_0 - z_n)}{\sqrt{(r_1 - r_0)^2 + (z_1 - z_0)^2} \sqrt{r_0^2 + (z_0 - z_n)^2}} \quad (5)$$

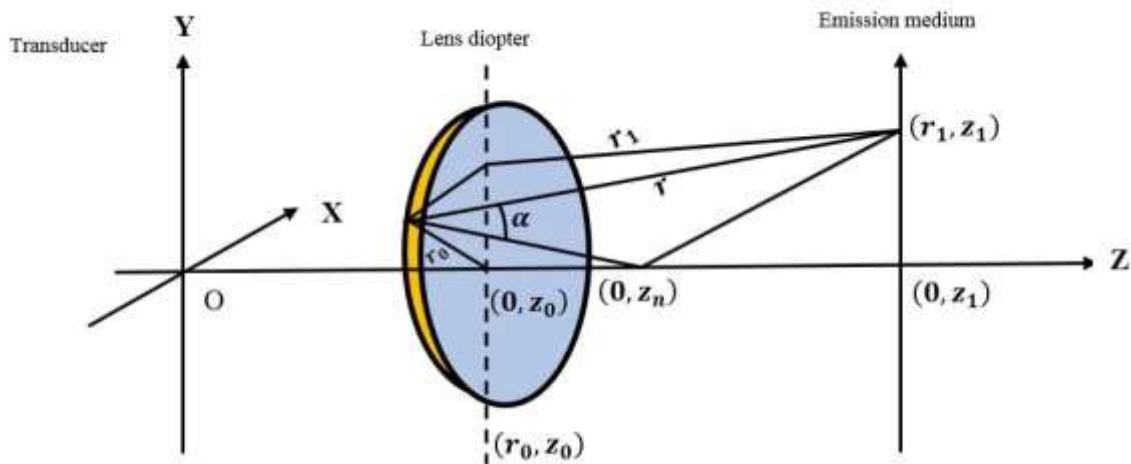


Fig.2. Geometry was adopted for the calculation. A field is radiated by a source surface of circular axisymmetric symmetry. F is the focal point.

It is worth noting that we are dealing with a carbon fiber composite sample, consisting of multiple anisotropic and heterogeneous plies. Using the theory of weighted volumes, the ply is considered to be a homogeneous anisotropic material. In each ply, the elastic constants have two quantities: one parallel to the ply and the other perpendicular to it. Additionally, we assign orientation to these quantities based on the orientation of the ply.

The reflected coefficient is:

$$r = \frac{(c_{11} - c_{22}) - j \left(\frac{c_{21} \cos \theta_0}{wz_0} - c_{12} w z_0 / \cos \theta_0 \right)}{(c_{11} + c_{22}) + j \left(\frac{c_{21} \cos \theta_0}{wz_0} - c_{12} w z_0 / \cos \theta_0 \right)} \quad (6)$$

Where θ_0 the angle of incidence z_0 is the acoustic impedance, the coefficients C_{ij} come from the global transfer matrix of the multilayer.

EXPERIMENTS

This section is divided into two main parts. The first part describes the experimental materials and measurement procedures, while the second part contains data for calculations.

Material of the study

The specimens analyzed in this study were manufactured at the Civil and Mechanical Engineering (GeM) laboratory at the University of Nantes, France. The samples manufactured are thin epoxy-carbon composite plates measuring $150 \times 150 \text{ mm}^2$, covered with a thin protective film. The specimens have four folds with a stacking sequence of $[0^\circ, 0^\circ, 0^\circ, 0^\circ]$. The individual ply thickness is 0.125 mm, and the stacking results in a final thickness of about 0.5 mm (Figure 3). During the manufacturing process, a piece of adhesive tape measuring $20 \times 20 \text{ mm}^2$ was inserted between the second and third ply to prevent delamination defects.

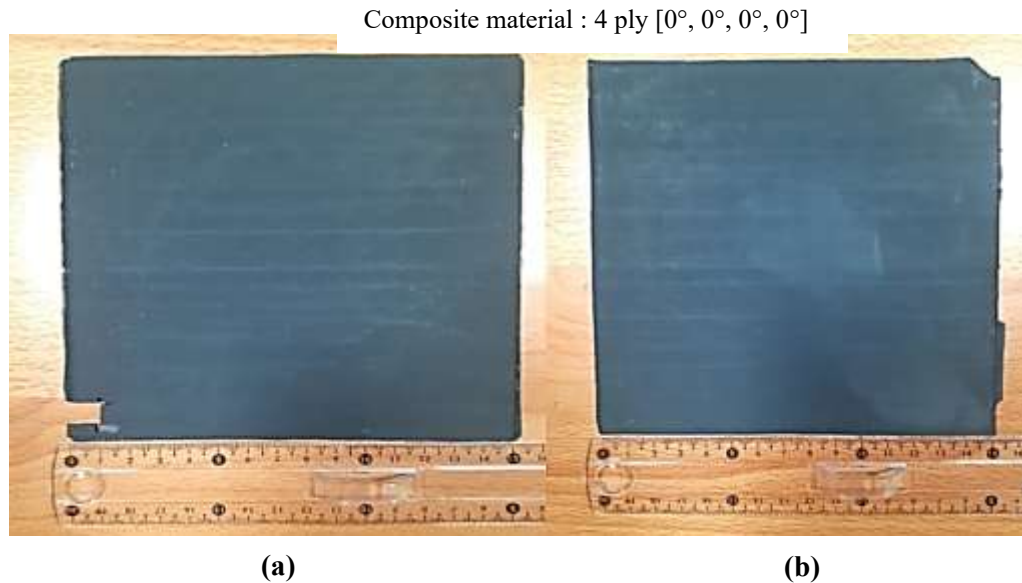


Fig.3. Carbon fiber composite plate: (a) without defect; (b) with delamination defect.

Experimental procedures

The experiments were conducted at the Industrial Techniques Research Center (CRTI) in Algiers, Algeria. The control was done by using an immersion ultrasonic scanner called “k-scan 95 krautkrämer” (Figure 4). The transducer used in the experiment was a focused type parametric (V 312) with a frequency of 10 MHz and a focal length of 20 mm.

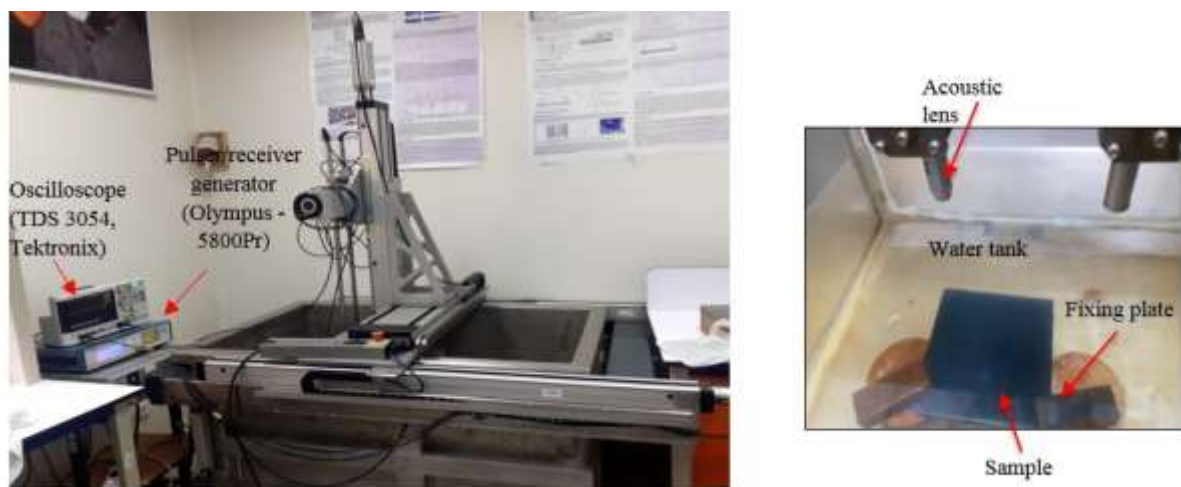


Fig. 4. Ultrasonic scanner.

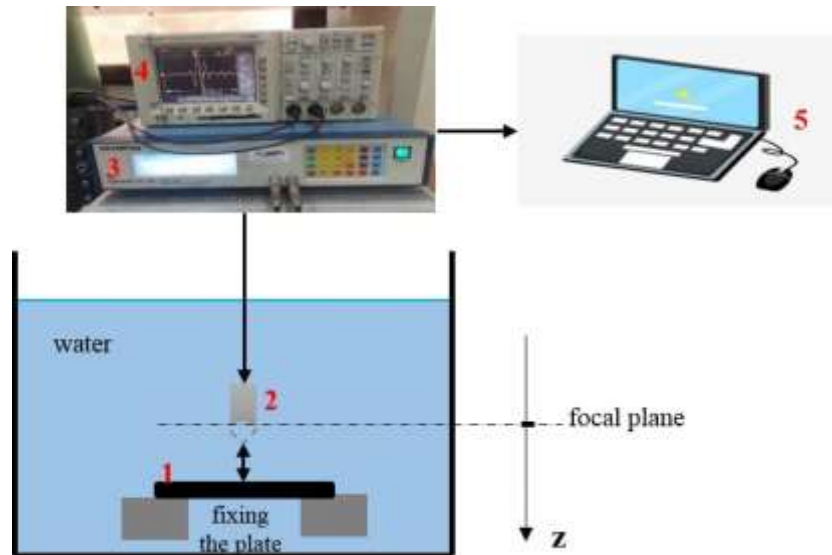


Fig. 5. Instrumental setup: 1- sample, 2- focused transducer, 3- pulser/receiver generator (Olympus 35-5800Pr), 4- oscilloscope (TDS 3054, Tektronix), 5- computer.

The experiment involves placing a transducer 20 mm above the sample (as shown in figure 5) so that the focus is on the surface of the sample. The transducer is then moved downward along the z-axis in increments of 0.13 mm using the scanner's mechanical motor system until it reaches the sample. Ultrasonic waves are emitted, which propagate through the water (couplant) and into the layered composite. At the interfaces within the composite, the emitted ultrasound waves are reflected. The transducer receives the reflected wave, converts it into an electrical pulse, and displays it on the screen of a digital oscilloscope. With each displacement of the transducer, the oscilloscope visualizes the oscillations of the received acoustic field, which is recorded in a file. All the amplitude values recorded as a function of the respective displacements constitute the acoustic field received by the transducer.

Two ultrasound characterizations were carried out. The first involved a carbon-fibre composite plate without any defects, while the second involved an equivalent plate containing an induced delamination defect. Table 2 presents the characteristics of the two plates.

Table. 2. Characteristics data of the two carbon-fibre composite plates.

Composite plate	
Composite type	Carbon/epoxy
Ply thickness	0.125mm
Plate dimensions	150×150 mm ²
Density	1530 kg/m ³
Number of ply	4
Longitudinal velocity	2429 m/s
Transverse velocity	1406 m/s
Type of defect	delamination
Defect dimensions	20×20 mm ²

The delamination defect is a 2 cm x 2 cm square piece of adhesive of unknown thickness that is created during composite manufacturing, as shown in figure 6.

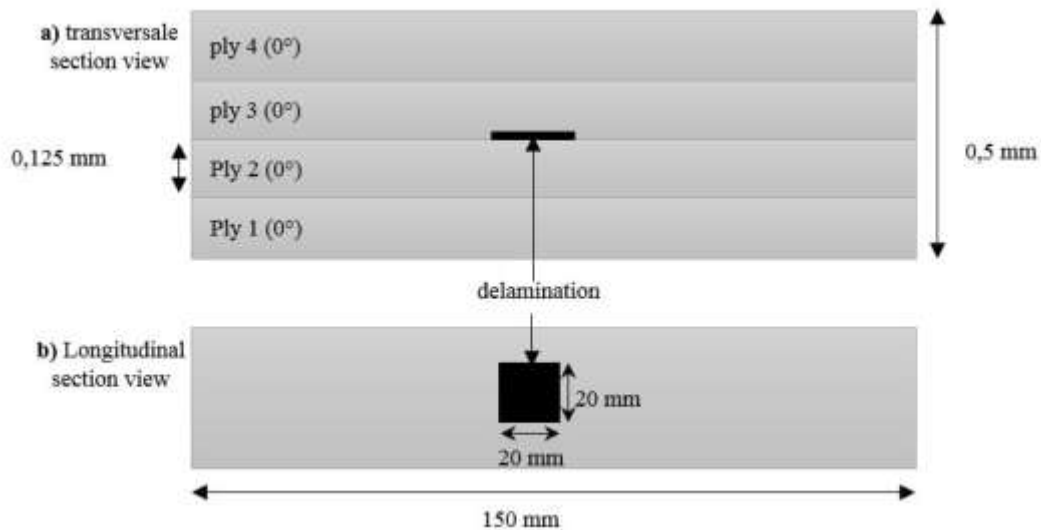


Fig. 6. Schematic 4-ply carbon/epoxy stack with delamination.

The objective of the experiment is to detect and measure the thickness of the delamination defect.

MEASUREMENTS AND SIMULATION RESULTS

The acoustic field received at the transducer is shown in figure 7 for the plate without defects $[0^\circ, 0^\circ, 0^\circ, 0^\circ]$ and in figure 8 for an equivalent plate $[0^\circ, 0^\circ, 0^\circ, 0^\circ]$ containing a delamination defect between the second and the third plies. The delamination is detected at $z=4.3$ mm, which corresponding the position of the delamination, if we take into account the width of the lens diopter which is 0.46 inch as well as point target focus (min 0.46 inch; max 2.1 inch) given by the manufacturer.

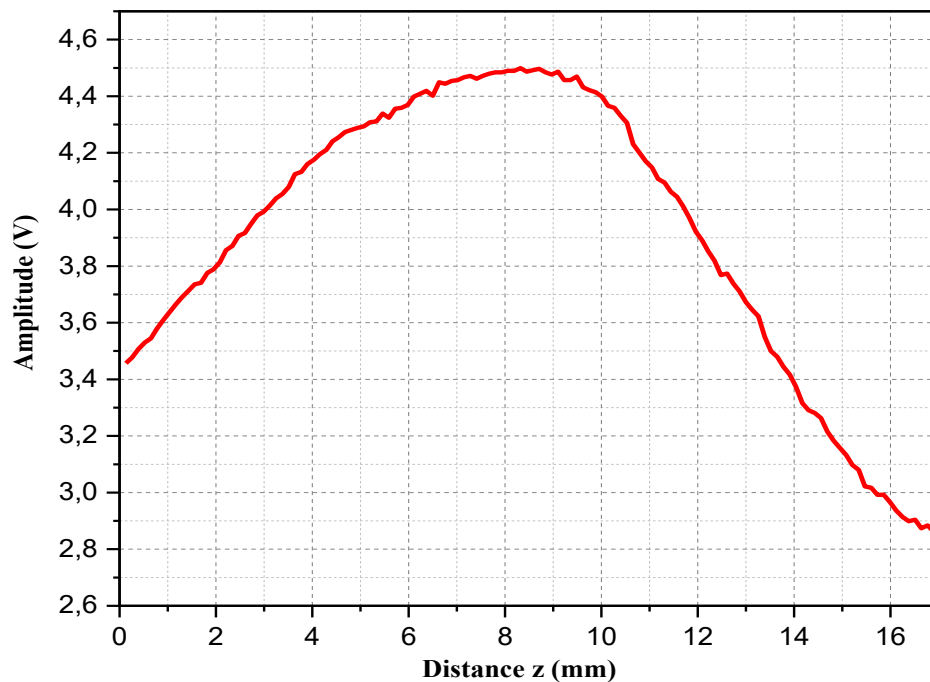


Fig.7. Received field – Plate without defect.

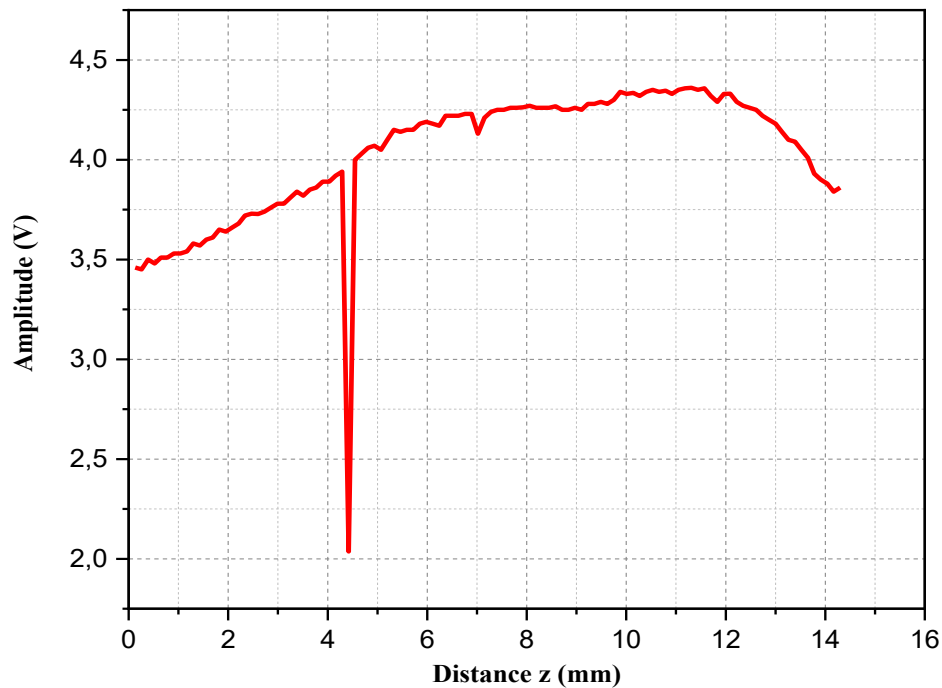


Fig. 8. Field received – plate with defect.

In order to simulate the acoustic field received at the transducer, we utilize a theoretical model that is based on ray theory [18]. The thickness of the delamination defect is taken as an input parameter, which is varied from 0.1 mm to 1 mm in increments of 0.1 mm to thoroughly examine the thickness of the actual defect by comparing the theoretical acoustic signature with that of the experimental data. The results of the simulation are displayed in figures 9 and 10.

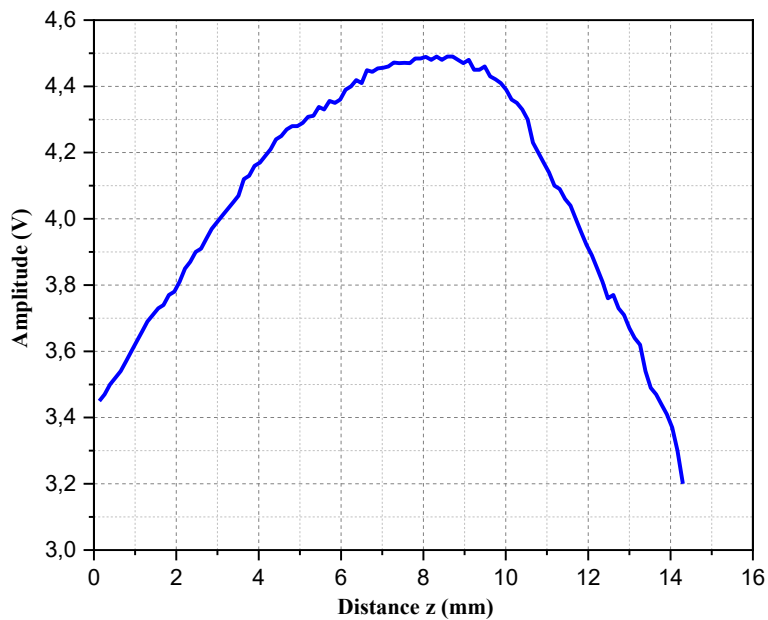


Fig. 9. Received field – plate without defect.

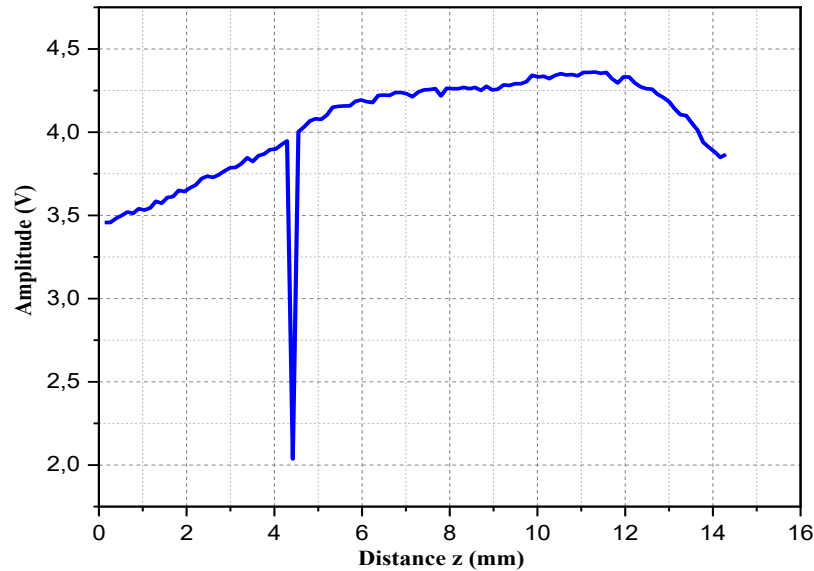


Fig. 10. Received field – plate with defect.

A comparison between the experimental results and those obtained by simulation can be seen in figures 11 and 12. The results show a strong agreement between the values of the acoustic field received by the transducer measured experimentally and those simulated by ray theory. This validates the developed model. Furthermore, the simulation model accurately reproduces the same results obtained by the experiment for the plate containing a delamination defect induced between the second ply and the third. The theoretical model also allowed us to define a thickness of 0.2 mm for the induced defect (pic width), which was previously unknown.

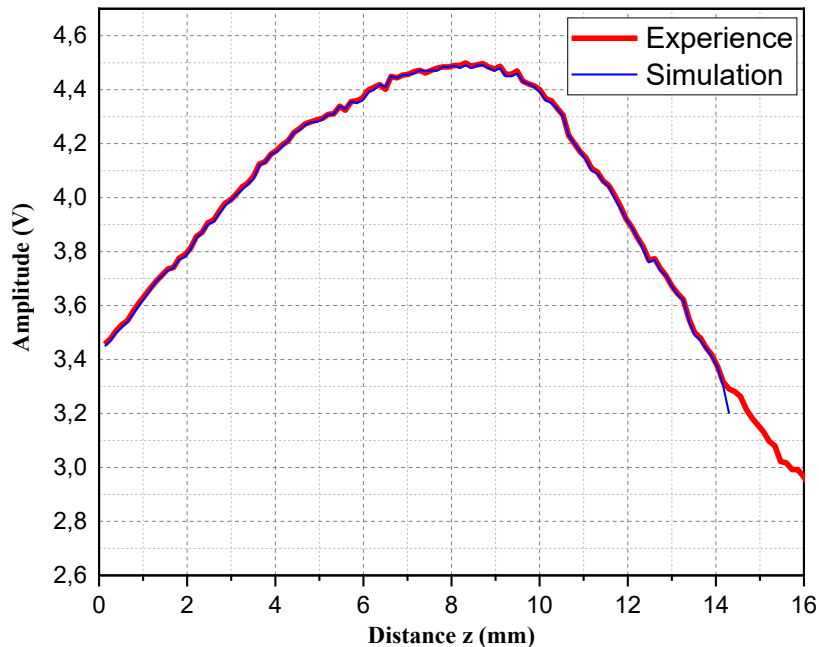


Fig. 11. Comparison between simulation and experimental results for a defect-free plate.

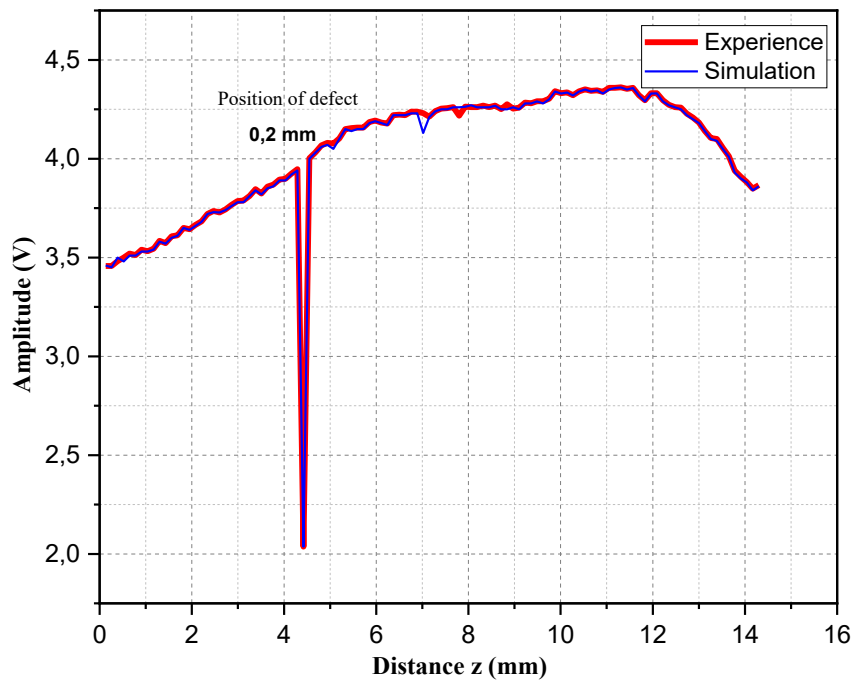


Fig. 12. Comparison between simulation and experimental results for a plate with a delamination defect.

C-SCAN IMAGE

To determine the size and shape of the defects, we used conventional ultrasound imaging techniques. This method involved a transmission immersion testing system, which was set up as shown in figure 13. To test small, flat parts, we used an automatic scanning system that involved a transport method using a cabinet. The cabinet was equipped with three carriages that moved along three axes (x, y, and z). The probe holder had two identical ultrasonic transducers with a frequency of 2.25 MHz that could be adjusted using two pinions: one for vertical orientation, and the other for landscape orientation. The transducers were connected to the ultrasonic pulser/receiver generator (Olympus 35 MHz-5800Pr). The detected signals were amplified and transferred to a digital oscilloscope (Tektronix TDS 2334).

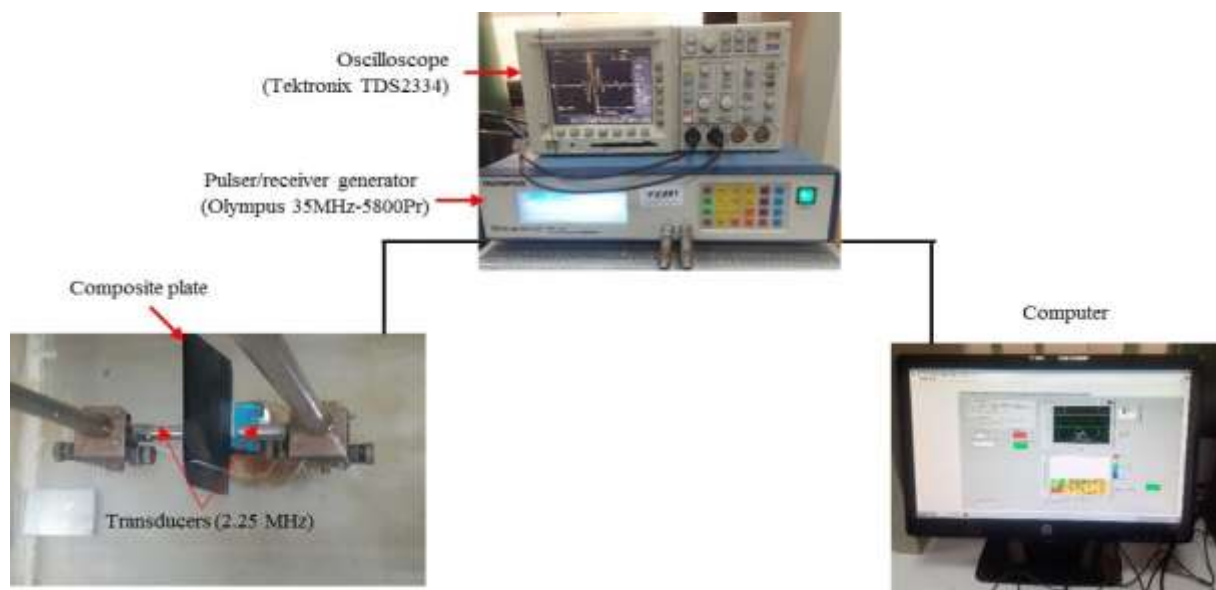


Fig. 13. Experimental setup used for the ultrasonic Transmission C-scan imaging.

Figure 14 presents the C-scan image depicting the delamination induced in the epoxy carbon laminate.

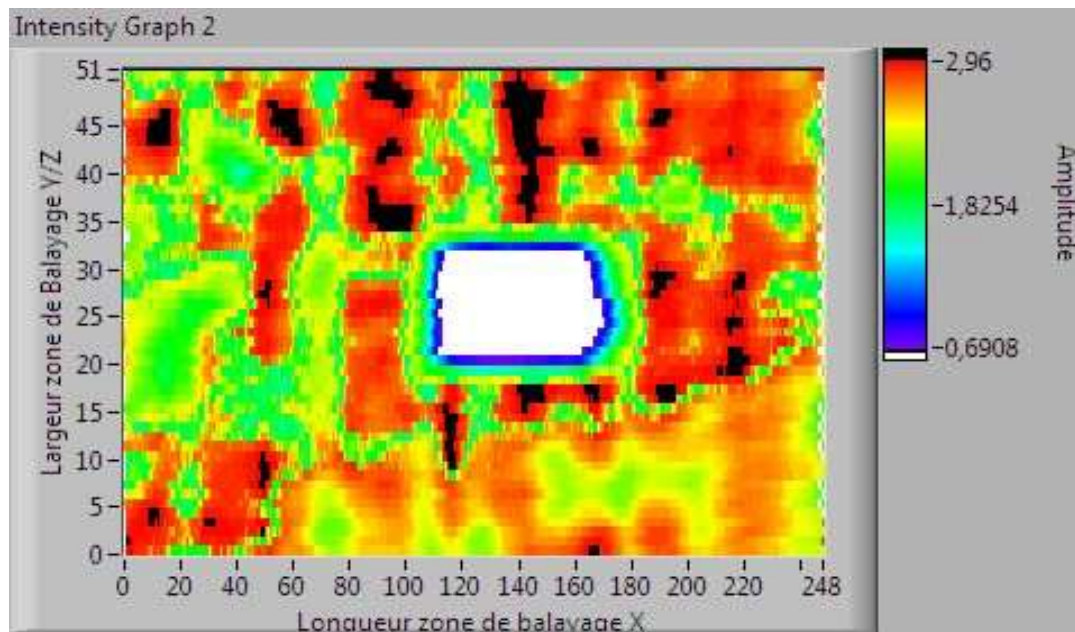


Fig.14. The C-scan image of delamination

According to the length and width of the scanning zone of the defect, the dimension of delamination calculated by the US scanner software was nearly square 21 mm long and 21 mm wide.

Conclusion

The immersion ultrasonic transducer method is an effective way to measure the thickness of carbon fiber composite plates. This technique is non-destructive and provides precise and reproducible results. We have also developed a numerical model that allows us to determine the thickness of delamination defects in these plates. In the future, we plan to simulate the localization of these defects at different locations between the plies. With the help of software integrated with the ultrasonic scanner, we will be able to measure the thickness of delamination defects quickly and locate them accurately.

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