GUIDED WAVES APPROACH FOR DAMAGE DIAGNOSIS IN GFRP LAMINATES

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In

CAD/CAM & Robotics

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July 2012

CERTIFICATE

This is to certify that the work in this thesis report entitled **"GUIDED WAVES APPROACH FOR DAMAGE DIAGNOSIS IN GFRP LAMINATES"** submitted in partial fulfilment of requirement for the award of **Master of Engineering Degree in CAD/CAM & Robotics** in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of work carried out by me under the guidance of **Mr Sandeep Sharma, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in part or full to any university or institute for the award of any degree.

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ABSTRACT

In the area of non-destructive testing, ultrasonic wave propagation testing has proved to be very effective tool for damage detection & evaluation of the health of subject. Ultrasonic testing uses transmission of high frequency stress waves into a material to detect imperfections or to identify changes in material properties. The most commonly used ultrasonic testing techniques include pulse echo and pulse transmission technique, where stress waves are introduced into subject structure. Pulse echo is used to locate the exact position of damage and pulse transmission is used to evaluate the presence & magnitude of damage. Relative comparison of wave signatures in healthy and damaged composite laminates could lead to an indication related to the health of specimen being tested.

Glass fibre-reinforced polymer (GFRP) laminated composites have been used as an alternative to other metals & alloys due to high strength-to-weight ratio, high stiffness-to-weight ratio, corrosion and fatigue resistance. These composites may be subjected to damages either due to manufacturing flaws like missing fibre, air-voids etc. or damages may develop under working condition.

This report presents the use of ultrasonic NDT techniques to detect the damage in GFRP laminates, submerged in water, with seeded defects in the form of notches, missing fibre and delamination. Negative spike pulse is used as an input signal to sending transducer through Pulser/Receiver system and transmitted pulse is received at the other end by receiving transducer. Ultrasonic waves are introduced at suitable angles to excite the different modes in the subject specimen in both pulse echo and through transmission technique.

The combination of pulse echo and pulse transmission voltage signals has been successfully used to detect the damage and localize the same by generating the tomograms of the specimen.

CONTENTS

CERTIFICATE ii
ACKNOWLEDGEMENT iii
ABSTRACT iv
LIST OF FIGURES viii
LIST OF TABLES xii
CHAPTER 1: INTRODUCTION 1
1.1 General 1
1.2 Non-Destructive Testing (NDT) 2
1.2.1 NDT Techniques [1] 2
1.2.2 Comparison of NDT techniques for composite defect detection 4
1.3 Ultrasonics as Structural Health Monitoring Tool 5
1.3.1 Introduction 5
1.3.2 Advantages of ultrasonic NDT [3] 6
1.3.3 Limitations of ultrasonic NDT [3] 6
1.3.4 Application of ultrasonic NDT technique 7
1.4 Modes of wave propagation [3] 7
1.5 Ultrasonic Guided waves 10
1.6 Terminology for ultrasonic wave propagation [2] 11
1.7 Reflection, refraction and mode conversion 13
1.8 Ultrasonic testing techniques 14
1.9 Tomography/Tomogram 18
1.10 Closure 18
CHAPTER 2: COMPOSITE MATERIALS 19
2.1 Introduction 19
2.2 Composite materials [5] 19
2.2.1 Constituents of composite [6] 20
2.2.2 Classification systems of composites [7] 20
2.2.3 Properties of composites 22
2.2.4 Advantages of composites 22
2.2.5 Disadvantages of composites 23

2.2.6 Types of fibre reinforced polymers 23
2.3 Glass Fibre Reinforced Polymer (GFRP) 23
2.3.1 Advantages and Disadvantages of GFRP 23
2.3.2 Applications of GFRP 23
2.4 Laminated composites 24
2.4.1 Properties that can be emphasized by lamination are 24
2.4.2 Applications of laminated composites 25
2.4.3 Methods of moulding for laminated composites [5] 25
2.5 Damage in laminated composite 26
2.5.1 Definition of Damage 26
2.5.2 Damage induced due to environmental degradation 27
2.5.3 Damage induced due to working condition 28
2.6 Objectives of the work 30
2.7 Closure 30
CHAPTER 3: LITERATURE REVIEW 31
3.1 Gaps in literature review 44
CHAPTER 4: EXPERIMENTAL DETAILS 45
4.1 Introduction 45
4.2 Fabrication of Glass Fibre Laminates 45
4.3 Specification and method of fabrication of the defected specimen 48
4.3.2 Specimen for Delamination 52
4.4 Experimental setup 54
4.5 Selection of the Frequency & Angle for damage detection 60
4.6 Work plan 62
4.7 Closure 62
Chapter 5: RESULTS and DISCUSSION 63
5.1 Introduction 63
5.2 Notch Defect evaluation 63
5.2.1 Notch defect across the fibre direction 63
5.2.2 Notch defect along fibre 68
5.3 Evaluation for missing fibre 70

5.3.1 Evaluation of the missing fibre defect according to varying length 71
5.3.2 Evaluation of the missing fibre defect according to the varying depth 73
5.4 Evaluation for delamination 79
5.4.1 Delamination of constant length (40 mm) 79
5.4.2 Evaluation for uneven delamination 82
Chapter 6: CONCLUSIONS 86
6.1 Evaluation for notch defect 86
6.2 Evaluation for missing fibre defect 86
6.3 Evaluation of delamination 87
6.4 Scope of future work 87
REFERENCES 88

LIST OF FIGURES

Figure 1.1: Principle of ultrasonics [2] 5
Figure 1.2: Propagation of Longitudinal waves [2] 7
Figure 1.3: Direction of Propagation of longitudinal and transverse waves [2] 8
Figure 1.4: Propagation of Transverse waves [2] 8
Figure 1.5: Propagation of surface waves [3] 9
Figure 1.6: Lamb Wave mode (a) Symmetric (S mode) (b) Anti-symmetric (A mode) [2] 10
Figure 1.7: Different types of guided waves in various problem geometries [4] 11
Figure 1.8: Reflection and Transmission of sound wave at normal incidence [3] 13
Figure 1.9:Snell's Law[3] 14
Figure 1.10: Principle of Ultrasonics 15
Figure 1.11: Pulse-echo principle [3] 16
Figure 1.12: Through transmission principle [3] 16
Figure 1.13: Three common modes of transmitter-receiver arrangement: pulse-echo, through transmission and pitch-catch [4] 17
Figure 2.1: Particle reinforced composites (Spheroidized steel and automobile tire) [8] 21
Figure 2.2: Fibre reinforced composites, a) continuous fibre-reinforced b) discontinuous aligned fibre reinforced c) discontinuous random-oriented fibre-reinforced [5] 21
Figure 2.3: Structural composites [8] 22
Figure 2.4: Laminated composites 24
Figure 2.5: (a) Fibre breakage (b) Matrix cracking (c) Interfacial shear failure [1] 29
Figure 2.6: Delamination [1] 29
Figure 3.1: Relative orientation of transmitter, receiver and plate specimen, (b) Schematic of the internal defects in five layers of the composite plates specimen 32
Figure 3.2: CFRP specimen (250 mm × 50 mm) with piezoceramic actuator and sensors 33
Figure 3.3: Experimental setup (a) Schematic, (b) instrumentation and (c) 5 × 5 cross-hole setup. 34
Figure 3.4: Tomogram of cross-ply laminate with one defect. 34
Figure 3.5: Tomogram of quasi-isotropic laminate with two defects. 35
Figure 3.6: The schematic mapping of fabricated Aluminium plate. 35

Figure 3.7: The lamb wave testing methods: a) pulse-echo technique and b) emission method.. 36
Figure 3.8: The waveforms of ultrasonic lamb wave in pulse-echo technique, a1 mode evaluated (defect to probe distance was 75 mm) 36
Figure 3.9: The waveforms of ultrasonic lamb wave in emission technique, s1 mode evaluated (defect to transmitter distance and defect to receiver distance was 50 mm) 36
Figure 3.10: The Drawing the DAC curve for defect evaluating by assessment the notch defects with the depth of 10%, 30% and 60% as reference defects. 36
Figure 3.11: The structure of the GLARE3-3/2 composite and the position of the defect. 37
Figure 3.12: Reconstructed tomographic image obtained with different techniques. 38
Figure 3.13: Ultrasonic C-scan of impact damages at the maximum damage ply: (a) 7 J on CPLT (b) 11 J on CPLT, (c) 8 J on QILT; and (d) 11 J on QILT. 38
Figure 3.14: Tomographic reconstruction of an anisotropic medium with simulated projection data: (a) schematic of the defective medium (b) with cross-hole configuration, (c) with modified cross-hole configuration, (d) Compensated modified cross-hole. 39
Figure 3.15: Schematic diagram for Lamb wave tomography. 39
Figure 3.16: Experimental setup 40
Figure 3.17: Experimental set for Laser based measurements for Lamb wave response on glass-epoxy composite samples with PWAS as embedded sensors. 40
Figure 3.18: Schematic of air-coupled ultrasonic technique 41
Figure 3.19: Wind turbine blade (a) with artificially made defects (b) A-scan (c) B-scan (d) C-scan. 42
Figure 3.20: (a) Geometry of the welded plate showing sensors and defects, (b) The tomogram generated by the SDC-based RAPID technique. 43
Figure 3.21: (a) Woven composite plate showing sensors and defects, (b) Tomogram of the impact damage in the composite plate. 43
Figure 4.1: Glass Fibre roll 45
Figure 4.2: Base and Hardener 45
Figure 4.3: Cutting of glass fibre 46
Figure 4.4: Pouring base into the container 47
Figure 4.5: Mixing of base and hardener 47
Figure 4.6: Applying epoxy on the glass fibre sheet 47

Figure 4.7: Front view of the specimen 48
Figure 4.8: Specimens after applying epoxy 48
Figure 4.9: Specimen 1 for notch defect 49
Figure 4.10: Notch defect 50
Figure 4.11: Specimen 2 for notch defect 50
Figure 4.12: Removed portion of the fibre 51
Figure 4.13: Missing fibre defect 51
Figure 4.14: Specimen for missing fibre defect of varying depth (a) layer 2 (b) layer 4 (c) Orthographic view 51
Figure 4.15: Orthographic views of specimen for missing fibre of varying length 52
Figure 4.16: Aluminium strip placed inside the laminate 53
Figure 4.17: Delamination 53
Figure 4.18: Orthographic views of specimen for uneven delamination 54
Figure 4.19: Ultrasonic experimental setup for testing in water 54
Figure 4.20: Immersion probes (0.5 MHz) 55
Figure 4.21: JSR pulse generator 56
Figure 4.22: Layout of JSR Pulse Generator 57
Figure 4.23: Four axis scanning setup 60
Figure 4.24: Ultrasonic experimental setup 60
Figure 4.25: Work Plan 62
Figure 5.1: Specimen with the notch 64
Figure 5.2: Percentage drop in voltage signal for notch defect at different angles 65
Figure 5.3: Through transmission signature for notch defect at angles (a) 22° (b) 24° (c) 26° 66
Figure 5.4: Tomogram for notch defect across the fibre 67
Figure 5.5: Through transmission signature for notch at angle 24° 69
Figure 5.6: Tomogram for notch defect along the fibre direction 70
Figure 5.7: Percentage drop in voltage signal for missing Fibre of varying length 72
Figure 5.8: Through transmission ultrasonic signature for missing fibre of varying length at angles (a) 24° (b) 26° 72
Figure 5.9: Tomogram for missing fibre defect of varying length at angle 15° 73
Figure 5.10: Percentage drop in voltage signal for missing fibre in layer 2 75

Figure 5.11: Through transmission signal for missing fibre defect in layer 2 75
Figure 5.12: Tomograms for missing fibre in layer 2 at angles (a) 0° (b) 15° (c) 20° 76
Figure 5.13: Percentage drop in voltage signal for missing fibre in layer 4 77
Figure 5.14: Through transmission signal for missing fibre defect in layer 4 77
Figure 5.15: Tomograms for missing fibre in layer 4 at angles (a) 0° (b) 10° (c) 15° (d) 20° 78
Figure 5.16: Percentage drop in voltage signal for delamination (length 40 mm) 80
Figure 5.17: Through transmission signal for delamination (length 40 mm) at angles (a) 22° (b) 24° (c) 26° (d) 28° 80
Figure 5.18: Tomograms for delamination (length 40 mm) in layer 4 at angles (a) 0° (b) 5° (c) 10° (d) 15° 81
Figure 5.19: Voltage signal for uneven delamination at different locations 83
Figure 5.20: Percentage drop in voltage signal for uneven delamination at different locations .. 83
Figure 5.21: Through transmission signal for uneven delamination 84
Figure 5.22: Tomogram for uneven delamation at angle 15° 84

LIST OF TABLES

Table 1.1: Comparison of NDT techniques for composite defect detection [1] 4
Table 1.2: Direction of propagation of particles for different waves [2] 10
Table 4.1: Specification of JSR Pulse Generator 58
Table 4.2: Configuration of Digitizer Card 59
Table 5.1: Voltage signal for notch defect at different angles 64
Table 5.2: Percentage drop in peak to peak voltage amplitude for notch defect 65
Table 5.3: Voltage signal for notch defect at different angles 68
Table 5.4: Percentage drop in voltage signal for notch defect 69
Table 5.5: Voltage signal for missing fibre of varying length 71
Table 5.6: Percentage drop in voltage signal for missing Fibre of varying length 72
Table 5.7: Voltage signal for missing fibre defect in layer 2 74
Table 5.8: Voltage signal for missing fibre defect in layer 4 77
Table 5.9: Voltage signal for delamination of 40 mm length 79
Table 5.10:Voltage signal for the uneven delamination 82
Table 5.11: Percentage drop in the voltage signal for uneven delamination 83

CHAPTER 1:
INTRODUCTION

1.1 General

As the design and construction of Mechanical structures continue to evolve, Fibre reinforced composite offers enormous potential for use in wide range of engineering applications, it is becoming imperative that these structures be monitored for their health. In order to meet this need, the discipline of Structural Health Monitoring (SHM) has emerged.

Damage to glass fibre-reinforced polymer composites may be due to manufacturing flaws like missing fibre, air-voids etc. or may develop under working condition due to environmental degradation or due to different loading conditions like delamination, fibre pull-out, cracks etc. which are very essential to be monitored.

Non-destructive testing has been practiced for many decades, with initial rapid developments in instrumentation spurred by the technological advances that occurred during World War II and the subsequent defence effort. Some other conventional examples of NDT involves testing of watermelon by thumping, earthen pot by tapping, train's wheel by hammering, ceramic tiles by ball drop method etc.

Cost effective & reliable damage evaluation is critical for utilization of composite materials. In the area of non-destructive testing, ultrasonic wave propagation testing has proved to be very effective tool for damage detection & evaluation. Ultrasonic testing uses transmission of high frequency stress waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo and pulse transmission technique where stress waves are introduced into the structure and reflections (echoes) are returned to a receiver from internal imperfections.

This chapter involves some introduction about Ultrasonic techniques as NDT tool to detect and evaluate the damage, which includes modes of wave propagation, testing techniques, methods for data representation and basic terminology.

1.2 Non-Destructive Testing (NDT)

As the name suggested, it is the method of monitoring the object without any destructive measures. NDT relies on the fact that a defect such as crack will modify the pitch or note sounded by an object when vibrating at its natural frequency. Hence almost instinctive act of even the modern engineer is to strike a suspected component with a sharp blow and listen for the ring indicating its “soundness”.

The field of Non-destructive testing (NDT) is a very broad, interdisciplinary field that plays a critical role in assuring that structural components and systems perform their function in a reliable and cost effective fashion. The term is generally applied to investigations of material integrity. These tests are performed in a manner that does not affect the future usefulness of the object or material. Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost-effectiveness.

The rapid growth in the use of non-destructive testing methods and techniques in the past few decades has resulted from demands by industry for improved quality and especially for critical requirements in the field of jet aircraft, supersonic flights, space research, missiles and nuclear energy.

A new challenge was thus presented to the non-destructive testing community. Detection was not enough. One needed to also obtain quantitative information about flaw size to serve as an input to fracture mechanics based predictions of remaining life. The need for quantitative information was particularly strong in the defence and nuclear power industries and led to the emergence of quantitative non-destructive evaluation (QNDE) as a new engineering/research discipline.

1.2.1 NDT Techniques [1]

Some of the commonly used NDT techniques are as follows:

Visual and Optical Testing: Visual inspection involves using an inspector's eyes to look for defects. The inspector may also use special tools such as magnifying glasses or mirrors gain access and more closely inspect the subject area.

Penetrant Testing: Test specimens are coated with visible or fluorescent dye solution. Excess dye is then wiped out from the surface, and a developer is applied. The developer acts as blotter, drawing trapped penetrant out of imperfections open to the surface. With visible dyes, vivid colour contrasts between the penetrant and developer make “bleed out" easy to see.

Magnetic Particle Testing (MT): In this method a magnetic field in a ferromagnetic material is induced and then dusting the surface with iron particles (either dry or suspended in liquid) is done. Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections, previewing a visual indication of the flaw.

Electromagnetic Testing (ET) or Eddy Current Testing: Eddy currents are generated in a conductive material by an induced alternating magnetic field and they flow in circles at just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the materials conductive and permeability properties, can be detected with the proper equipment.

Radiography (RT): Radiography involves the use of penetrating gamma or X radiation to examine parts and products for imperfections. An X-ray generator or radioactive isotope is used as a source of radiation. The resulting shadow graph shows the dimensional features of the part. Possible imperfections are indicated as density changes on the film in the same manner as medical X-ray shows broken bones.

Ultrasonic Testing (UT): Ultrasonic testing use transmission of high-frequency stress waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, where stress waves are introduced intoa test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces.

Acoustic Emission Testing (AE): When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions". As in ultrasonic testing; acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity, rate, and location.

Leak Testing (LT): Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas penetrant techniques, and/or a simple soap-bubble test.

Electromagnetic Acoustic Transducers (EMATs): They generate and detect ultrasonic waves via electromagnetic coupling between the EMAT and the metal samples. They operate via the Lorentz force or magneto elastic mechanisms or both simultaneously.

X-Ray Fluorescence (XRF): X-ray fluorescence is one of the methods for NDT. The equipment contains radioactive sources or a low voltage x-ray generator, which sends out radiation. The exposed material then sends temporarily element specific radiation back, generating energy. As every element has its own atomic structure, this reflection will generate a different energy level for every element. This energy is measured and detected, thus identifying the alloy elements.

Infrared Thermography: It is a fast NDT inspection method which does not influence the process and maps the temperature differences of any object in a range from -50ºC to 1500ºC. Instead of detecting the temperature point by point, thermo graphic camera is able to detect the temperature across a complete surface. This gives an excellent image of local temperature differences.

1.2.2 Comparison of NDT techniques for composite defect detection

NDE METHODS	DEFECT TYPES							
	Delamination	Voids	Moisture	Resin Thickness	Fiber Waviness	Fiber Breakage	Porosity	Matrix Cracking
Visual Testing (VT)	1	0	0	0	1	0	0	0
Acoustic Impact Testing (AIT)	2	1	0	0	1	1	0	0
Penetrant Testing (PT)	0	0	0	0	0	1	0	1
Ultrasonic Testing (UT)	2	1	1	-	-	1	0	0
Radiographic Testing (RT)	2	2	1	2	2	2	2	2
Thermographic Testing (TIR)	2	1	1	-	-	-	-	0
Eddy Current Testing (ET)	0	0	-	0	2	2	0	0
Optical Methods (Shearography)	2	2	-	-	2	2	-	-
Acoustic Emission (AE)	1	0	0	0	0	2	0	2

2 Generally Detectable, 1 Limited Detectability, 0 Not Detectable, - Detectability unknown

Table 1.1: Comparison of NDT techniques for composite defect detection [1]

From above comparison it is clear that Ultrasonic is effective tool for detection of various defects. When coupled with other factors like portability, real time acquisition, cost etc.

Ultrasonic technique is best suitable for defect detection in composites. In some areas its potentialis still need to be investigated.

1.3 Ultrasonics as Structural Health Monitoring Tool

1.3.1 Introduction

The human ear is not sensitive to sound, having frequency above 20,000 Hz. The sound which we cannot hear due to its high frequency is known as ultrasound or ultrasonics. NDT is essentially a low power application of ultrasonics. The frequencies commonly used for ultrasonic testing range from 100 kHz to 25 MHz. Ultrasonic waves are mechanical waves and need a medium for their propagation. In their propagation, the particles in the medium vibrate to and fro in the direction of motion or perpendicular to the direction of motion, about a mean position. The particles do not travel with the wave but only the disturbance or the movement of particle moves forward through the medium. The relation of velocity of sound wave to frequency and wavelength can be given by

$$c = f \lambda$$

Where c is the velocity of sound (m/s), f is the frequency in cycles/s (Hz) and λ is the wavelength (m).

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more**.** Figure 1.1 gives information about setup of ultrasonic testing in flaw detection.

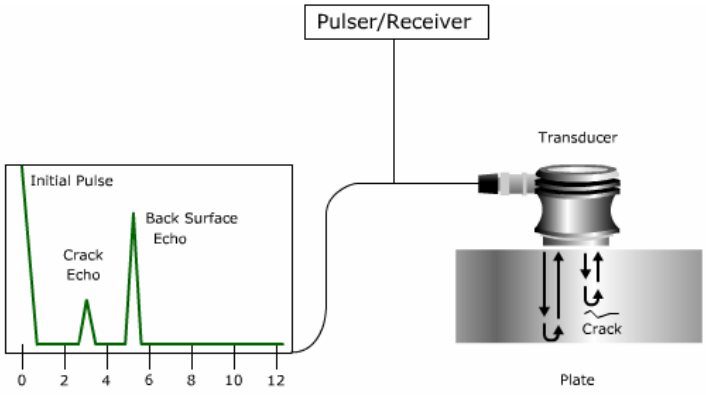


Figure 1.1: Principle of ultrasonics [2]

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high

voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. This is how defect is detected from the time of flight of received signal (t) and knowing the velocity (v) of wave in a particular solid medium, the defect can be located as

$$D=vt/2$$

This is called pulse echo technique. It is assisted by through transmission in which two transducer are used for testing the object specimen. The magnitude of damage is found from the change in amplitude of the through transmission signal. This is one of the best non-destructive testing methods where ultrasonic wave is send into the structure to find the location and magnitude of the defect. Ultrasonic wave propagation varies with change in the medium in which the wave propagates.

1.3.2 Advantages of ultrasonic NDT [3]

1. High sensitivity
2. High penetration power
3. High accuracy
4. Needs only one surface to be accessible for inspection.
5. Easy portability of equipment.
6. Not much expensive.
7. Immediate results
8. Fast response
9. No special safety precautions needed.

1.3.3 Limitations of ultrasonic NDT [3]

1. Good technical knowledge required.
2. Penetration not so good for coarser structure material like casting and stainless steel.
3. Not very much suited for inspection of rough, irregular in shape, very small parts, very thin or non-homogeneous test objects.

4. Couplants are needed for efficient transfer of ultrasonic energy from the transducer to the job.
5. Reference standards are required for regular calibration of the equipment and for characterizing of flaws.

1.3.4 Application of ultrasonic NDT technique

1. Discontinuity measurement
2. Thickness measurement
3. Study of elastic constant
4. Study of metallurgical structure
5. Evaluation of the processing parameter for their optimization.

1.4 Modes of wave propagation [3]

The ultrasonic waves propagate in a number of ways in a medium. Wave propagation depends on material properties of the structure. On the basis of the mode of particle displacement, these waves can be classified as:

1. Longitudinal or Compressional waves (L-waves).
2. Transverse or Shear waves (S-waves)
3. Surface or Rayleigh waves.
4. Lamb or Plate waves
5. Creeping or Head waves

1) Longitudinal or Compressional waves

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation as shown in the **Figure 1.2**. Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move.

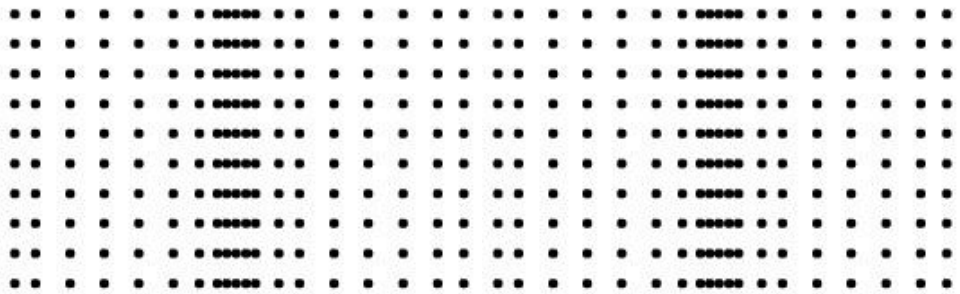


Figure 1.2: Propagation of Longitudinal waves [2]

Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements.

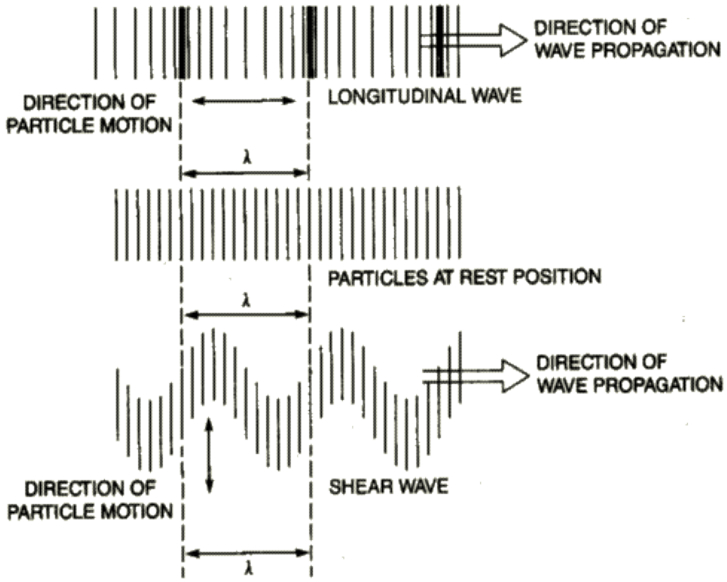


Figure 1.3: Direction of Propagation of longitudinal and transverse waves [2]

2) Transverse or Shear wave

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation as shown in the **Figure 1.3**. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves.

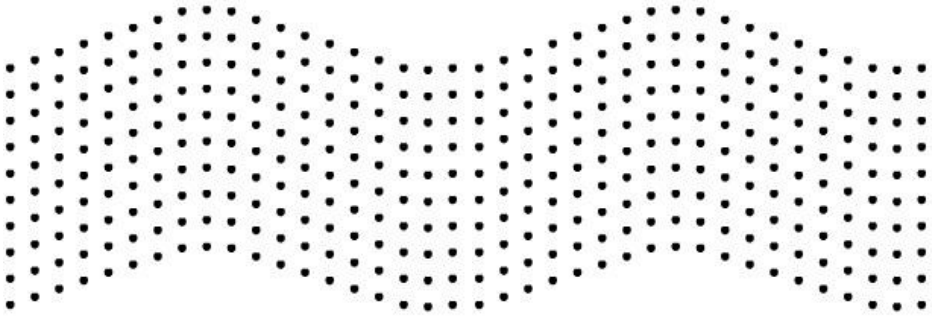


Figure 1.4: Propagation of Transverse waves [2]

Infact, shear waves are usually generated in materials using some of the energy from longitudinal waves. For the propagation of transverse waves, it is necessary that each particle exhibits a strong force of attraction to its neighbours, so that as a particle moves back and forth it pulls its

neighbor with it. Due to this reason air and water do not support transverse waves. In gases, the forces of attraction between molecules are so small that shear waves cannot be transmitted. The same is true of a liquid, unless it is particularly viscous or is present as a very thin layer. The velocity of transverse waves is approximately 50% of the longitudinal wave velocity for the same material.

3) Surface (or Rayleigh) waves

Surface (or Rayleigh) waves travel on the surface of a relatively thick solid material penetrating to a depth of one wavelength. Rayleigh waves are useful because they are very sensitive to surface defects and they follow the surface around curves. These waves can travel along the flat and curved surfaces. These waves are subjected to less attenuation in a given material than the longitudinal or transverse waves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.

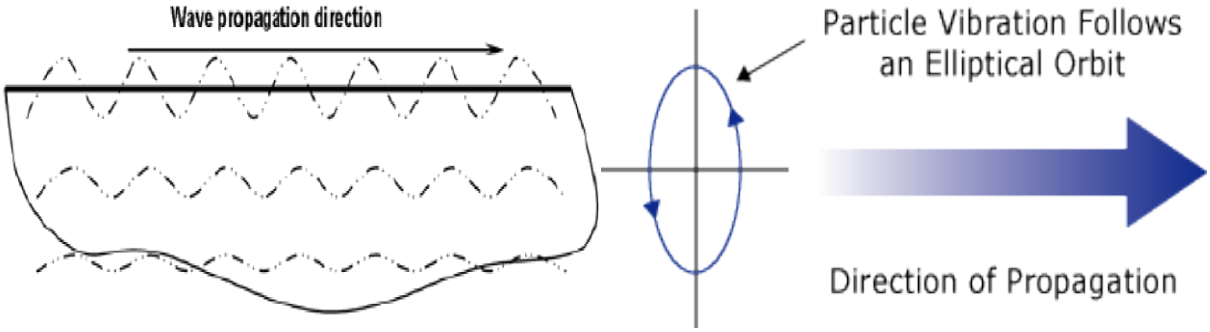


Figure 1.5: Propagation of surface waves [3]

4) Lamb waves

Plate or Lamb waves can be propagated only in very thin metals. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibrational waves that travel through the entire thickness of a material. Propagation of lamb waves depends on the density and the elastic material properties of a component. They are also influenced a great deal by the test frequency and material thickness. With lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical as shown in the **Figure 1.6**. The complex motion of the particles is similar to the elliptical orbits for surface waves. Symmetrical lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the extensional mode because the wave is “stretching and compressing” the plate in the wave motion direction. Wave motion in the symmetrical mode is most efficiently

produced when the exciting force is parallel to the plate. The asymmetrical lamb wave mode is often called the "flexural mode" because a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.

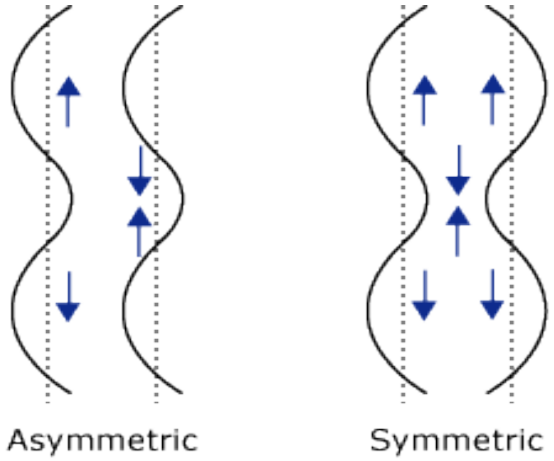


Figure 1.6: Lamb Wave mode (a) Symmetric (S mode) (b) Anti-symmetric (A mode) [2]

5) Creeping waves

These waves are also called head waves. The behaviour of creeping waves is similar to that of longitudinal waves. They travel as fast as longitudinal waves and the creeping waves should not be misunderstood as moving slowly. These are generated parallel to scanning surface, enabling detection of surface breaking defects. These have limited range and as these travel just below the surface and not on the surface, so the couplant has no influence.

Wave Types in Solids	**Particle Vibrations**
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface – Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave – Lamb	Component perpendicular to surface (extensional wave)

Table 1.2: Direction of propagation of particles for different waves [2]

1.5 Ultrasonic Guided waves

Guided waves are the acoustic waves travelling in the vicinity of the material boundaries. Boundaries not only influence the propagation but they actually guide the wave along the

structure. If the structure is a homogenous half-space then the guided wave propagating along the surface of the half-space is called Rayleigh wave. Waves propagating through a plate type structure with two parallel stress-free boundaries are known as Lamb waves.

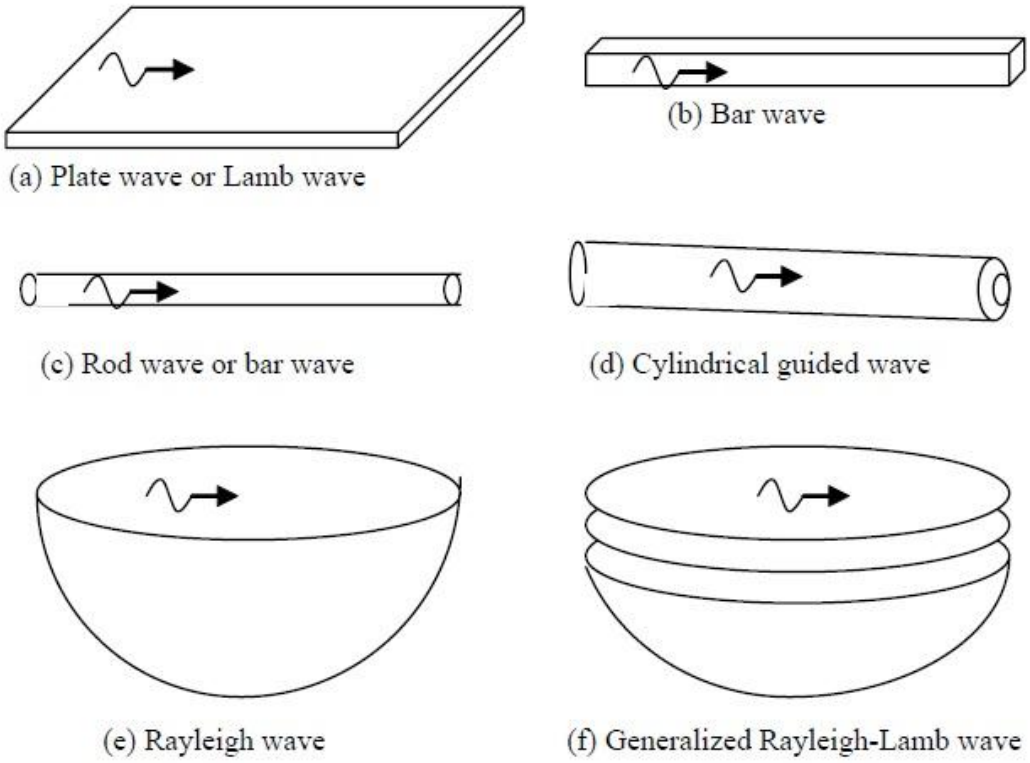


Figure 1.7: Different types of guided waves in various problem geometries [4]

Elastic waves propagating through a hollow cylinder or pipe are called cylindrical guided waves. Since for a cylinder the two stress-free surfaces – inner and outer surfaces – are parallel to each other as in a plate, sometimes the cylindrical guided waves are also called Lamb waves. When guided waves propagate through a rod or bar they are known as bar waves. **Figure 1.7** shows different types of guided waves propagating through various structures that are also known as waveguides.

1.6 Terminology for ultrasonic wave propagation [2]

Ultrasonic waves are simply organized mechanical vibrations travelling through a medium, which may be in any state of matter. These waves travel through a given medium at a specific speed or velocity, in a predictable direction, and when they encounter a boundary with a different medium they will be reflected or transmitted according to simple rules. This is the principle of physics that underlies ultrasonic flaw detection.

Some of the generally used terms to define the ultrasonic waves are

1. **Frequency:** All sound waves oscillate at a specific frequency, or number of vibrationsor cycles per second, which we experience as pitch in the familiar range of audible sound. Human hearing extends to a maximum frequency of about 20,000 cycles per second (20KHz), while the majority of ultrasonic flaw detection applications utilize frequencies between 500 KHz to 10 MHz. At frequencies in the Megahertz range, sound energy does not travel efficiently through air or other gasses, but it travels freely through most liquids and common engineering materials.
2. **Wave Speed:** The speed of a sound wave varies depending on the medium through which it is travelling, affected by the medium's density and elastic properties. Different types of sound waves will travel at different velocities.
3. **Wavelength (λ)**: It is the distance between any two corresponding points in the wave cycle as it travels through a medium. Wavelength is related to frequency and velocity by the simple equation

   $$\lambda = c/f$$

   Where, λ = wavelength, c = sound velocity, f = frequency

   In ultrasonic flaw detection, the generally accepted lower limit of detection for a small flaw is one-half wavelength, and anything smaller than that will be invisible. In ultrasonic thickness gauging, the theoretical minimum measurable thickness is one wavelength.
4. **Acoustic impedance (Z):** Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid. The Acoustic impedance (Z) of a material is defined as the product of its density (ρ) and acoustic speed in medium

   $$Z = \rho/c$$

   Acoustic impedance is important in determining acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.
5. **Reflection and Transmission Coefficients:** Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances (Z) of the materials on each side of the boundary as shown in the **Figure 1.8**. This difference in Z is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and

another. The fraction of the incident wave intensity that is refracted can be derived because particle velocity and local particle pressures must be continuous across the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected can be calculated with the equation below. The value produced is known as the reflection coefficient.

Reflection coefficient,

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_{2V_2} - \rho_{1V_1}}{\rho_{2V_2} + \rho_{1V_1}}$$

Transmission coefficient,

$$T = \frac{2Z_2}{Z_2 + Z_1} = \frac{\rho_{2V_2} - \rho_{1V_1}}{\rho_{2V_2} + \rho_{1V_1}}$$

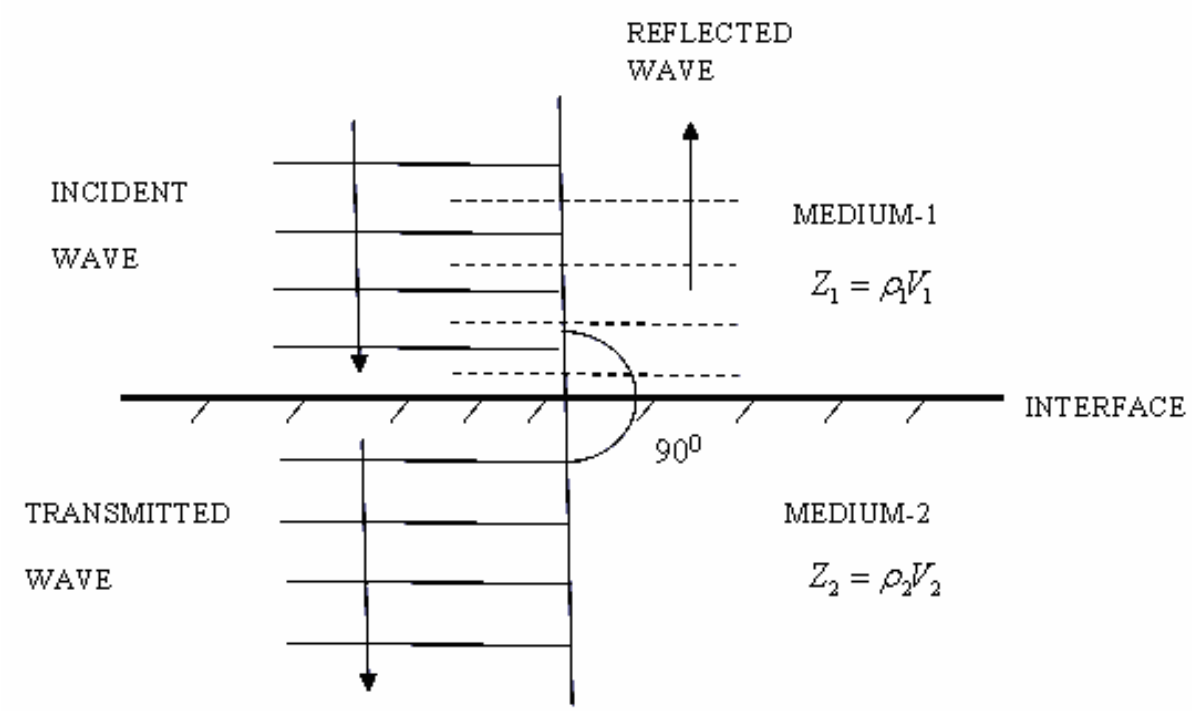


Figure 1.8: Reflection and Transmission of sound wave at normal incidence **[3]**

1.7 Reflection, refraction and mode conversion

When sound travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal wave hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. Mode conversion occurs when a wave encounters an interface between materials of different acoustic

impedances and the incident angle is not normal to the interface. When sound waves pass through an interface between materials having different acoustic velocities, refraction takes place at the interface. The larger the difference in acoustic velocities between the two materials, the more the sound is refracted. Notice that the shear wave is not refracted as much as the longitudinal wave. This occurs because shear waves travel slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as longitudinal waves but it is between the incident and refracted longitudinal waves. Also note that when a longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave. This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material. Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows.

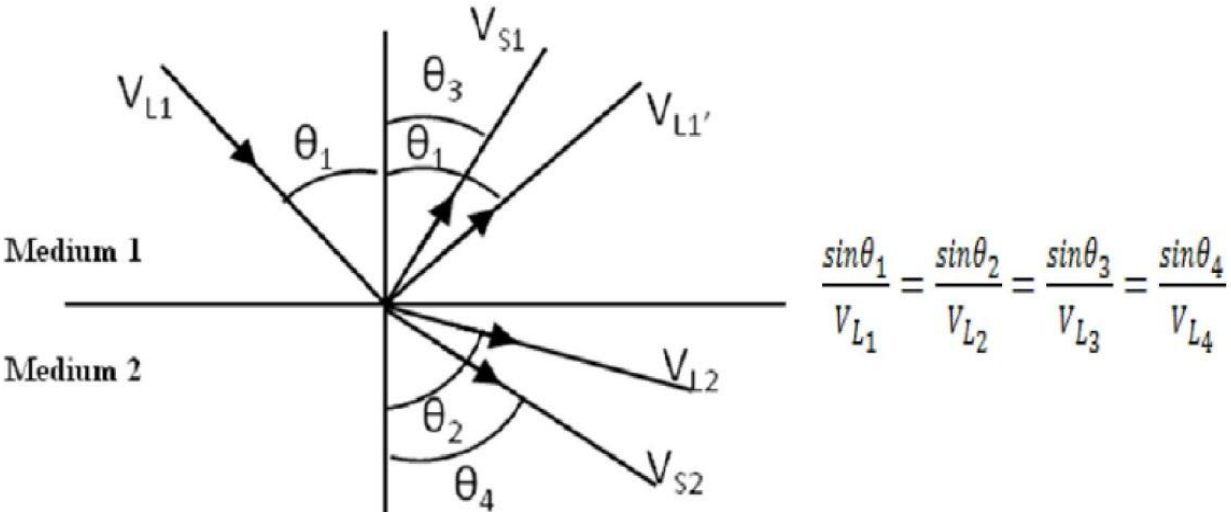


Figure 1.9:Snell's Law[3]

Where:

VL1 - is the longitudinal wave velocity in material 1

VL2 - is the longitudinal wave velocity in material 2

VS1 - is the shear wave velocity in material 1.

VS2 - is the shear wave velocity in material 2.

1.8 Ultrasonic testing techniques

Ultrasonic energy striking at an interface of two different materials, either at normal or at inclined incidence, is partially reflected back or partially transmitted into the other medium. It is the transmitted part of energy which is utilized in inspection work. Depending on conditions of

test and information required, a number of techniques are used for the ultrasonic inspection. Various techniques of ultrasonic most commonly used are:

1. Pulse echo method
2. Through transmission method
3. Two transducer method
4. Resonance method

All the above entailed techniques are discussed below:-

1. **Pulse Echo Method**

   In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer, where the reflected energy is converted into an electrical signal as shown in the **Figure 1.10, Figure 1.11** and **Figure 1.13**. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.

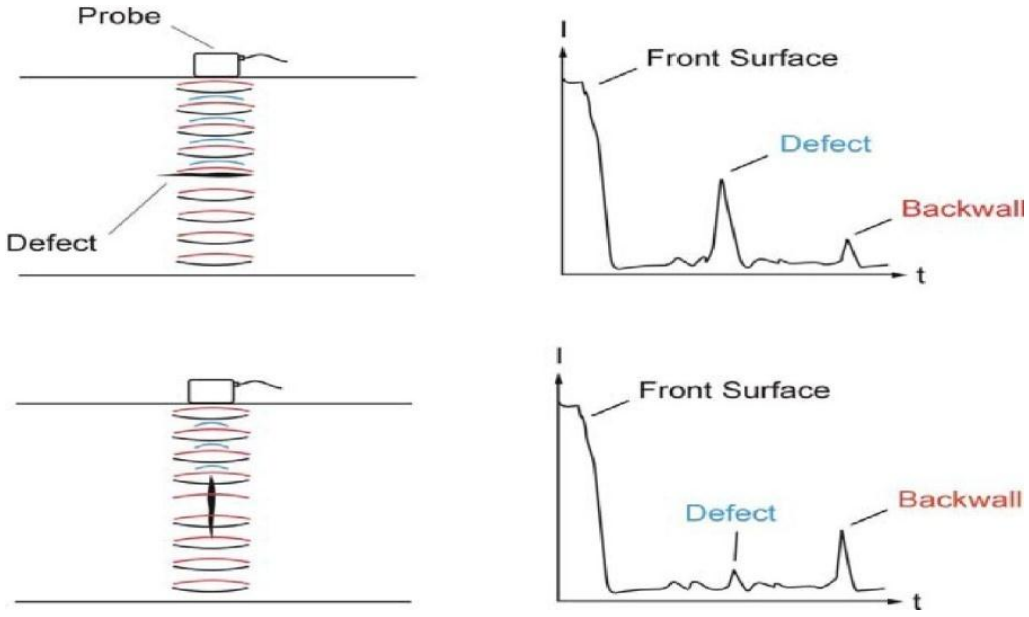


Figure 1.10: Principle of Ultrasonics

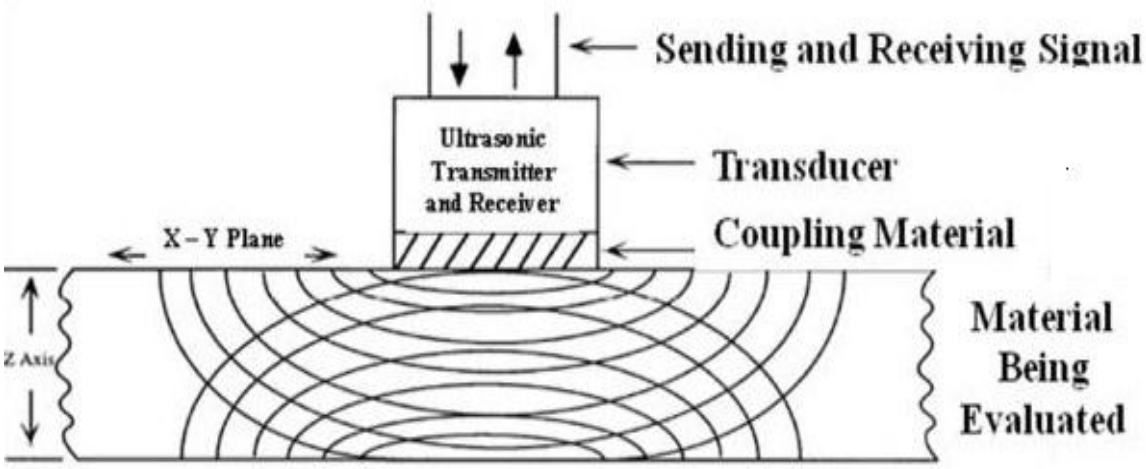


Figure 1.11: Pulse-echo principle [3]

2. Through Transmission Method

In the through-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side as shown in the **Figure 1.12** and **Figure 1.13**. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

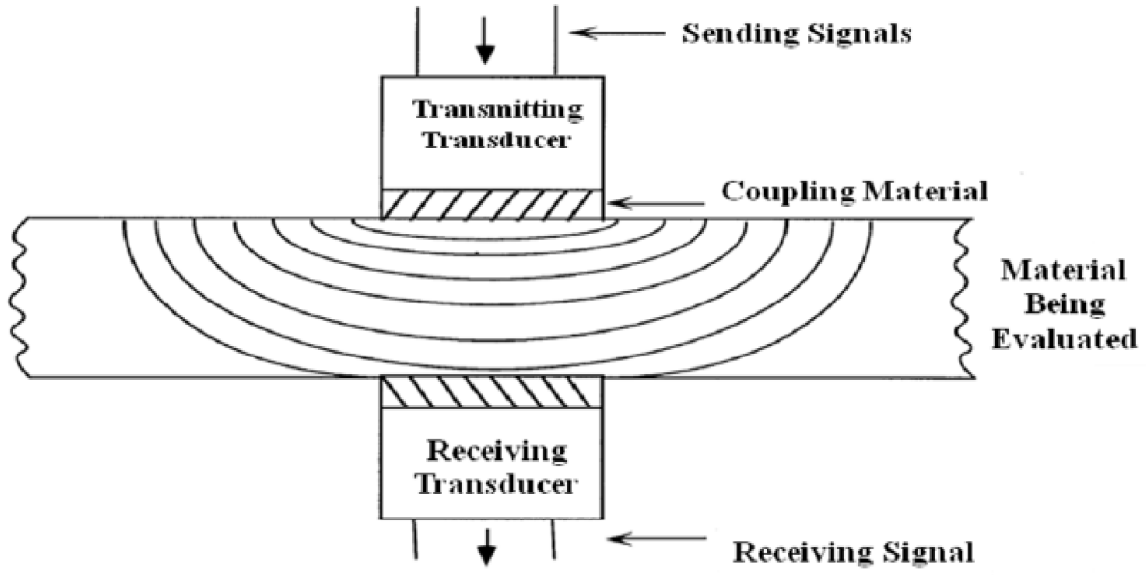


Figure 1.12: Through transmission principle [3]

3. Two Transducer Method

The pulse echo method can be used with either single or double crystal unit in single transducer unit the probe acts as both transmitter and receiver. In two transducer arrangement, one transmits and other receives the ultrasonic waves. These are placed on same side of specimen. Pulse wave is send into the specimen by the transducer T and the echoes reflected from the back surface or any defect are received by the transducer R and displayed on the flaw detector screen. For specific applications like wall thickness measurement special type of transducers in which the transmitting and the receiving crystals are housed in a single unit are also used. These transducers are popularly known as 'twin' or T-R probes.

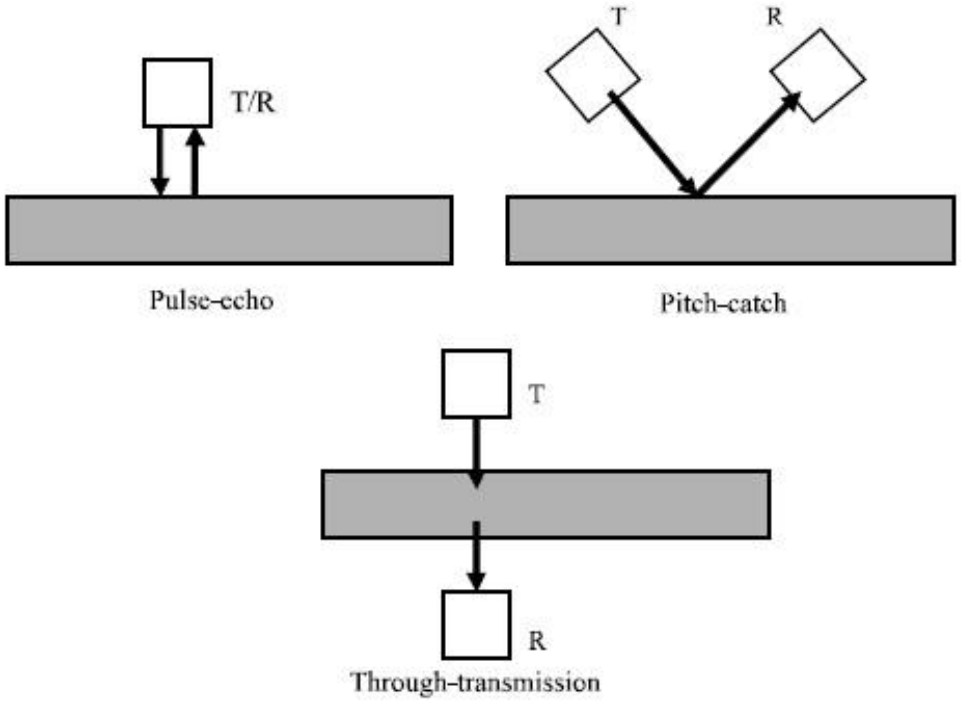


Figure 1.13: Three common modes of transmitter-receiver arrangement: pulse-echo, through transmission and pitch-catch [4]

4. Resonance Method

The method uses resonance phenomenon to measure the material thickness or to determine the quality of bonding in two materials. In a situation that the thickness of the material equals half the wavelength of the sound or it's multiple, resonance takes place. The frequency of the continuous longitudinal waves transmitted in the material is varied till

standing waves are set up in the material. Presence of resonance is indicated by an increase in amplitude as the probe is moved and a change of resonant frequency is seen, which cannot be accounted for by a change in material thickness, if any, it is usually an indication of discontinuity.

From the above methods, Pulse Echo method is mostly used in Ultrasonic testing to find location of defect in specimen and Through Transmission is mostly used in testing using ultrasonic to find the magnitude of the defect in specimen.

1.9 Tomography/Tomogram

Tomography refers to imaging by sections or sectioning, through the use of any kind of penetrating wave. A device used in tomography is called a tomograph, while the image produced is a tomogram. The word tomography is derived from the Greek *tomē* ("cut") or *tomos* ("part" or "section") and *graphein* ("to write"). The method is used in radiology, archaeology, biology, geophysics, oceanography, materials science, astrophysics, quantum Information, and other sciences. In most cases it is based on the mathematical procedure called tomographic reconstruction.

1.10 Closure

In this chapter the use of Ultrasonic as NDT tool has been discussed in detection & evaluation of defects. Ultrasonic Bulk and Guided technique have been successfully implemented for detection and evaluation of various defect geometries.

Following chapter gives introduction to composite material, laminates, their applications, and manufacturing method. The common type of damage that can occur in composites has also been discussed.

CHAPTER 2:
COMPOSITE MATERIALS

2.1 Introduction

Fibre reinforced composite offers enormous potential for use in wide range of engineering applications, ranging from sports goods to advanced aircraft structures. Glass fibre-reinforced polymer (GFRP) have been used as an alternative to steel & other metals due to high strength to weight ratio, high stiffness-to-weight ratio, corrosion and fatigue resistance.

The main environmental factors for the deterioration of GFRP are temperature, sunshine, water/moisture, alkalinity and load. Most of the early durability tests were carried out with reference to application of FRP (Fibre Reinforced Polymer) in aerospace.

Damage to Glass fibre-reinforced polymer composites may be due to manufacturing flaws like missing fibre, air-voids etc. or may develop under working condition due to environmental degradation or due to different loading conditions like delamination, fibre pull-out, cracks etc.

This chapter gives introduction about composites, types of fibre reinforced polymers, laminate composites, methods of manufacturing the composites & commonly occurring damage to composite structures.

2.2 Composite materials [5]

Composite materials are combination of two or more materials (reinforcing elements, fillers, and composite matrix binder), differing in form or composition on a macro scale. The constituents retain their identities, that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

The purpose of composites is to allow the new material to have strengths from both materials, often times covering the original material's weaknesses. Most of the products we see every day are made from *monolithic* materials. That means the individual components consist of a single material (an unreinforced plastic), or a combination of materials that are combined in such a way that the individual components are indistinguishable (a metal alloy). Some common composite materials include concrete, fibre glass, mud, bricks, and natural composites such as wood, rock etc.

2.2.1 Constituents of composite [6]

The individual materials that make up composites are called constituents. Most composites have two constituent materials

a) Resin or matrix
b) Reinforcement

The reinforcement is usually much stronger and stiffer than the matrix, and gives the composite its good properties. The matrix holds the reinforcements in an orderly pattern. Because the reinforcements are usually discontinuous, the matrix also helps to transfer load among the reinforcements.

2.2.2 Classification systems of composites [7]

There are two classification systems of composite materials. One of them is based on the matrix material (metal, ceramic and polymer) and the second is based on the material structure.

2.2.2.1 Classification I

1. **Metal matrix composites (MMC)**

Metal Matrix Composites are composed of a metallic matrix (aluminium, magnesium, iron, cobalt, copper) and a dispersed ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) phase.

2. **Ceramic matrix composites(CMC)**

Ceramic Matrix Composites are composed of a ceramic matrix and embedded fibres of other ceramic material (dispersed phase).

3. **Polymer matrix composite(PMC)**

Polymer Matrix Composites are composed of a matrix from thermo-set (Unsaturated Polyester (UP), Epoxy (EP)) or thermoplastic (Polycarbonate (PC), Polyvinylchloride, Nylon, Polystyrene) and embedded glass, carbon, steel or Kevlar fibres (dispersed phase).

2.2.2.2 Classification II

1) Particle-reinforced Composites

It consists of a matrix reinforced by a dispersed phase in form of particles.

a. Composites with random orientation of particles.
b. Composites with preferred orientation of particles. Dispersed phase of these materials consists of two-dimensional flat platelets (flakes*),* laid parallel to each other.

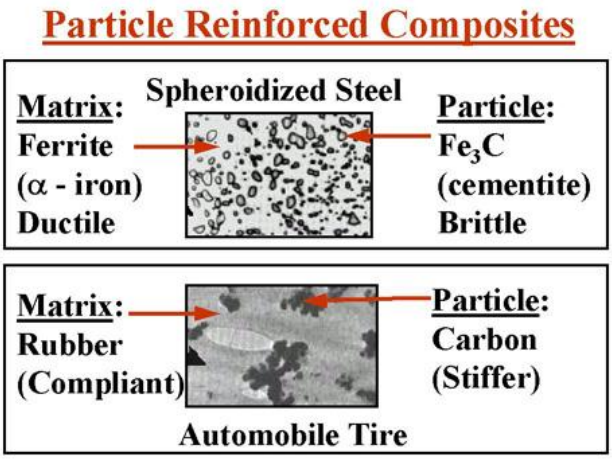


Figure 2.1: Particle reinforced composites (Spheroidized steel and automobile tire) [8]

2) Fibre-Reinforced Composites

a. Short fibre reinforced composites: Short fibre reinforced composites consist of a matrix reinforced by a dispersed phase in form of discontinuous fibres (length < 100 *diameter).

i. Composites with random orientation of fibres.

ii. Composites with preferred orientation of fibres.

3. **Long-fibre reinforced composites:** Long-fibre reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibres.

i. Unidirectional orientation of fibres.

ii. Bidirectional orientation of fibres (woven).

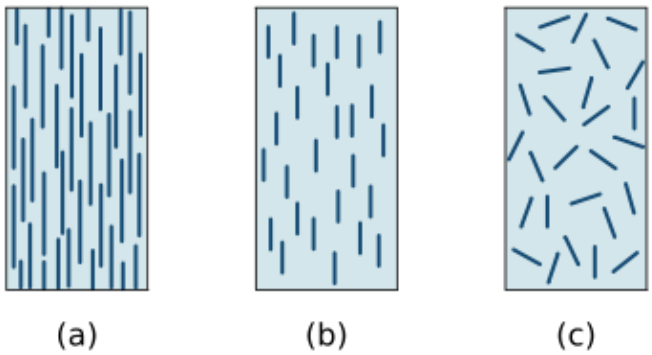


Figure 2.2: Fibre reinforced composites, a) continuous fibre-reinforced b) discontinuous aligned fibre reinforced c) discontinuous random-oriented fibre-reinforced [5]

3) Laminate Composites

The most common form in which fibre-reinforced composites are used in structural applications is called a laminate, which is made by stacking a number of thin layers of fibres and matrix and consolidating them into the desired thickness. Fiber orientation in each layer as well as the stacking sequence of various layers in a composite laminate can be controlled to generate a wide range of physical and mechanical properties for the composite laminate.

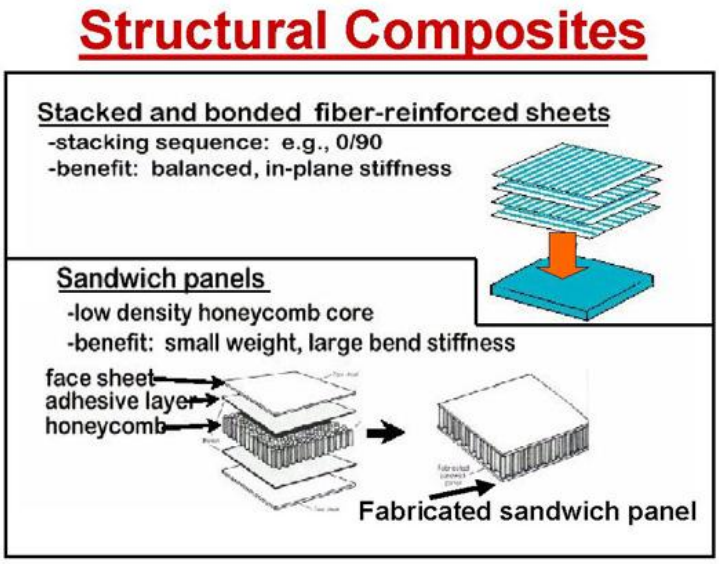


Figure 2.3: Structural composites [8]

2.2.3 Properties of composites

Composites have superior properties as compared to conventional metals & alloys.

1. High strength to weight ratio.
2. Light in weight
3. High resistance to corrosion, chemicals and other weathering agents.
4. They can be moulded to any shape and size with required mechanical properties in different directions.

2.2.4 Advantages of composites

1. Good dimensional stability
2. Low dielectric
3. Corrosion resistance
4. Less weight

2.2.5 Disadvantages of composites

1. High production cost
2. Difficult to repair
3. Design analysis must consider many variables.
4. Low inter-laminar strength
5. Poor conductivity

2.2.6 Types of fibre reinforced polymers

1. Carbon Fibre Reinforced Polymer (CFRP)
2. Glass Fibre Reinforced Polymer (GFRP)
3. Boron Fibre Reinforced Polymer (BFRP)
4. Aramid Fibre Reinforced Polymer (AFRP)

2.3 Glass Fibre Reinforced Polymer (GFRP)

Glass fibre reinforced polymers sheets are being increasingly used in rehabilitation and retrofitting of concrete structures as an alternative to steel in concrete due to their high strength to weight ratio and corrosion and fatigue resistance. Ease of handling and application at site are added advantages. It depends upon their properties and chemical composition. Of the different types of glass fibres, E-Glass is mostly used for reinforcement due to its high strength and electrical resistivity. Glass fibres have high strength and temperature resistance, but it is the low cost that makes GFRP the most popular. Depending on the application, there are 4 types of resin used with fibre glass- polyester, vinyl ester, epoxy and phenol.

2.3.1 Advantages and Disadvantages of GFRP

The principal advantages of glass fibres are low cost, high tensile strength, high chemical resistance, and excellent insulating properties. The disadvantages are relatively low tensile modulus and high density (among the commercial fibres), sensitivity to abrasion during handling (which frequently decreases its tensile strength), relatively low fatigue resistance, and high hardness (which causes excessive wear on moulding dies and cutting tools).

2.3.2 Applications of GFRP

1. Pods, domes and architectural features where a light weight is necessary.
2. Bodies for automobiles, such as the Chevrolet Corvette and Studebaker Avanti.
3. Aircraft wings and fuselage sections.

4. FRP tanks and vessels. FRP is used extensively to manufacture chemical equipment, tanks and vessels.
5. F-broadcasting antennas are often mounted inside a glass-reinforced plastic cylinder on the pinnacle of a broadcasting tower Housings for radar systems

2.4 Laminated composites

The most common form in which fibre-reinforced composites are used in structural applications is called a laminate, which is made by stacking a number of thin layers of fibres and matrix and consolidating them into the desired thickness. Fiber orientation in each layer as well as the stacking sequence of various layers in a composite laminate can be controlled to generate a wide range of physical and mechanical properties for the composite laminate. Laminate composites provide increased mechanical strength in two directions and only in one direction, perpendicular to the preferred orientations of the fibres or sheet, mechanical properties of the material are low. Laminated fibre reinforced composite materials are a hybrid class of composite materials involving both fibrous composite materials and lamination techniques. Purpose of lamination is to tailor the directional dependence of strength and stiffness of a composite material to match the loading environment of the structural element.

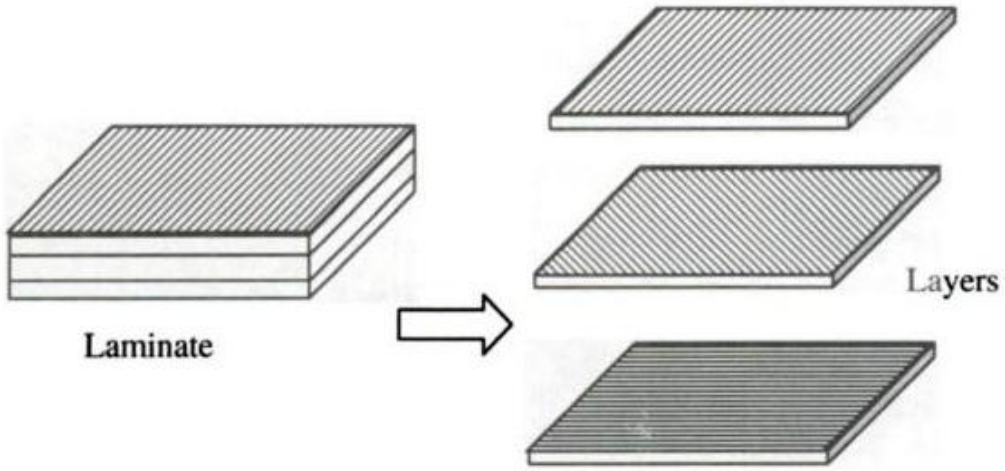


Figure 2.4: Laminated composites

2.4.1 Properties that can be emphasized by lamination are

1) Strength
2) Stiffness
3) Low weight

4) Corrosion resistance
5) Wear resistance
6) Thermal insulation
7) Acoustical insulation

2.4.2 Applications of laminated composites

1) Rocket motor cases, boat hulls, aircraft wing panels, tennis rackets, golf club shafts, etc.
2) Helicopter rotor blades are made of laminated composites and sandwich structures.
3) Aircraft blades are made up of carbon laminates, automobiles use composites for drive shafts manufacturing.

For the present study, characteristics of laminates with two ply have been used.

2.4.3 Methods of moulding for laminated composites [5]

1) **Hand lay-up operation:** In hand lay-up operation resin is mixed with a catalyst or hardener if working with epoxy, otherwise it will not cure (harden) for days/ weeks. Next, the mould is wetted out with the mixture. The sheets of fibre glass are placed over the mould and rolled down into the mould using steel rollers. The material must be securely attached to the mould; air must not be trapped in between the fibre glass and the mould. Additional resin is applied and possibly additional sheets of fibre glass. Rollers are used to make sure the resin is between all the layers, the glass is wetted throughout the entire thickness of the laminate, and any air pockets are removed. The work must be done quickly enough to complete the job before the resin starts to cure. Various curing times can be achieved by altering the amount of catalyst employed.
2) **Spray lay-up operation:** The fibre glass spray lay-up process is similar to the hand lay-up process but the difference comes from the application of the fibre and resin material to the mould. Spray-up is an open moulding composites fabrication process where resin and reinforcements are sprayed onto a mould. The resin and glass may be applied separately or simultaneously "chopped" in a combined stream from a chopper gun. Workers roll out the spray-up to compact the laminate. Wood, foam or other core material may then be added, and a secondary spray-up layer imbeds the core between the laminates. The part is then cured, cooled and removed from the reusable mould.

3) **Autoclave moulding:** A process using a two-sided mould set that forms both surfaces of the panel. On the lower side is a rigid mould and on the upper side is a flexible membrane made from silicone or an extruded polymer film such as nylon. Reinforcement materials can be placed manually or robotically. They include continuous fibre forms fashioned into textile constructions. Most often, they are pre-impregnated with the resin in the form of unidirectional tapes. In some instances, a resin film is placed upon the lower mould and dry reinforcement is placed above. The upper mould is installed and vacuum is applied to the mould cavity. The assembly is placed into an autoclave pressure vessel. This process is generally performed at both elevated pressure and elevated temperature. The use of elevated pressure facilitates a high fibre volume fraction and low void content for maximum structural efficiency.

4) **Pultrusion operation:** Pultrusion is a manufacturing method used to make strong light weight composite materials, in this case fibre glass. Fibres (the glass material) are pulled from spools through a device that coats them with a resin. They are then typically heat treated and cut to length. Pultrusions can be made in a variety of shapes or cross-sections such as a W or S cross-section. The word pultrusion describes the method of moving the fibres through the machinery. It is pulled through using either a hand over hand method or a continuous roller method. This is opposed to an extrusion which would push the material through dies.

For the present experimental work, laminated specimens have been prepared using hand lay operation.

2.5 Damage in laminated composite

2.5.1 Definition of Damage

In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state. Damage may adversely affect the current or future performance of these systems. As an example, a crack that forms in a mechanical part produces a change in geometry that alters the stiffness characteristics of that part. Depending on the size and location of the crack and the loads applied to the system, the adverse effects of this damage can be either immediate or may take some time before they alter

the system's performance. In terms of length scales, all damage begins at the material level and then under appropriate loading scenarios progresses to component and system level damage at various rates. In terms of time scales, damage can accumulate incrementally over long periods of time such as that associated with fatigue or corrosion damage accumulation.

2.5.2 Damage induced due to environmental degradation

The change in properties of structure due to moisture absorption and temperature change is called degradation due to hygro-thermal loading.

The influence of environmental factors, such as elevated temperatures, high humidity, corrosive fluids, and ultraviolet (UV) rays, on the performance of polymer matrix composites is of concern in many applications. These environmental conditions may cause degradation in the mechanical and physical properties of a fibre-reinforced polymer because of one or more of the following reasons: -

1. Physical and chemical degradation of the polymer matrix, for example, reduction in modulus due to increasing temperature, volumetric expansion due to moisture absorption, and scission or alteration of polymer molecules due to chemical attack or ultraviolet rays. However, it is important to note that different groups of polymers or even different molecular configurations within the same group of polymers would respond differently to the same environment.
2. Loss of adhesion or de-bonding at the fibre–matrix interface, which may be followed by diffusion of water or other fluids into this area. In turn, this may cause a reduction in fibre strength due to stress corrosion.
3. Moisture absorption leads to changes in the thermo physical, mechanical and chemical characteristics of the epoxy matrix by plasticization and hydrolysis. These changes in the polymer structure lower both the elastic modulus and the glass transition temperature. At the same time, moisture wicking along the fibre matrix interface degrades the fibre matrix bond, resulting in loss of micro structural integrity. The net effect of moisture absorption is the deterioration of matrix-dominated properties such as compressive strength, inter-laminar shear strength, fatigue resistance and impact tolerance .These factors lead to reduced damage tolerance and lack of long-term durability.
4. When a fibre-reinforced composite material is exposed to a Hygro-thermal environment and mechanical loads, changes in material properties are expected. These changes in

material properties are connected to an irreversible material degradation. The moisture may affect the laminates through chemical changes such as relaxation and oxidation of the matrix material. A cyclic moisture environment exposed to a laminate may cause damage such as de-bonding at fibre/matrix interfaces and continuous cracks.

5. Other damage modes that can occur in a fibre-composite laminate are transverse matrix cracks, delamination and fibre fracture. The results of chemical changes and mechanical damage in general affect the overall material properties, e.g. elastic modulus, hygrothermal expansion coefficients, diffusion coefficients. Usually one of the first observed damage modes in a laminated composite is matrix cracking. These cracks are in general not critical for final failure, but if they are connected to a surrounding moisture environment more rapid moisture absorption may be expected for the cracked laminate. The accelerated moisture absorption in a cracked material exposed to humid air is a result of the faster diffusion in air compared to the diffusion speed in the composite material. Faster moisture uptake may also develop a faster material degradation. This makes it important to know the moisture absorption behavior in a cracked laminate.

2.5.3 Damage induced due to working condition

1. Matrix cracking (tensile or shear)
2. Fibre breakage
3. Delamination (ply separation)
4. Fibre De-bonding / Fibre Pull Out

Matrix Cracking

Matrix cracking is the regularly the initial mode of failure and if severe enough will lead to delamination of the plies and eventual failure of the laminate. Although matrix cracking is very localized it can be very difficult to detect. The energy required for matrix cracking is relatively low, for a brittle carbon / epoxy composite.

Fibre Fracture

It is commonly known that at the point of fibre fracture during loading the composite material will generally fail catastrophically. If large enough, local stress concentrations at the tip of a matrix crack are able to initiate cracking of the adjacent reinforcing fibres. Fibre failure is largely dependent on the materials characteristics and can occur through many types of damage initiation, i.e. transverse impact loading or compression fatigue cycling.

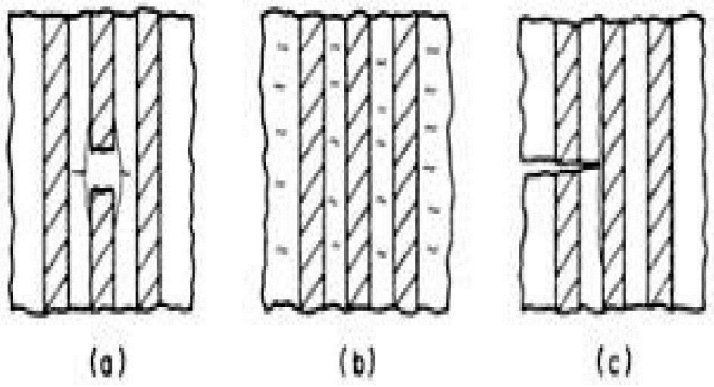


Figure 2.5: (a) Fibre breakage (b) Matrix cracking (c) Interfacial shear failure [1]

Delamination

Delamination in fibre reinforced polymer composites (FRPC) are commonly caused by bad manufacturing or impact damage and result in a significant reduction of compressive strength. Dependent on the initiation point of delamination within a material there can be two modes of delamination. If the initiation point is near to the surface of the sample, local delamination can occur, in this case the plies above and below the initiation point separate. Global delamination is a result of internal delamination where the plies move in the same direction, if the composite is under compression loading this can result in the composite buckling.

Figure 2.6: Delamination [1]

Fibre De-bonding / Fibre Pull Out

Fibre de-bonding / pull out are attributed to the frictional sliding between the interface of the fibre and matrix. At the tip of an advancing crack fibres can fracture and fail, if the crack continues to advance along the length of the fibre the fibre is pulled away from the surrounding

matrix. If the stresses around the de-bonding site are large enough and frictional forces are exceeded then this can result in the fibre being completely pulled out of the matrix.

2.6 Objectives of the work

Fibre reinforced composite offer enormous potential for use in wide number of engineering applications, ranging from sports goods to advanced aircraft structures. The superior stiffness and strength properties of fibre composites can be utilized to manufacture complex components with lower weight at reduced cost. During the manufacturing of composites, composite may be damaged due to presence or introduction of unwanted defects such as air-voids, resin rich areas, missing fibre, delamination, fibre crack etc. Their effect on the overall structural integrity of the component may be serious.

Clearly, there is a strong need to identify as well as characterize the various types of damage that occur in composite materials during manufacture and operational service. Ultrasonic as NDT technique has established itself as a complete NDT tool for damage identification and localization. The objective of the proposed study is to generate and investigate the propagation of ultrasonic waves through the composite laminates subjected to various damages. Damage diagnosis in the group presence, localization and extent of various types of simulated damages is investigated by the analysis and comparison of wave signatures of healthy and damaged composite specimens.

2.7 Closure

In this chapter composite material, laminates, their applications, and manufacturing method have been discussed.

Following chapter deals with previous research work done in the area of damage evaluation in composites with the help of ultrasonic testing. Literature survey has been carried out and discussed.

CHAPTER 3:
LITERATURE REVIEW

This chapter presents a review of literature on utilization of ultrasonic guided waves for damage defection in composites. This gives an idea of study carried out in this area till date.

Alleyne & Cawley [6] discusses the selection of the appropriate mode and frequency range for different inspection requirements and reviews the possible methods of excitation, response measurement and signal processing. It is usually desirable to transmit a single, non-dispersive mode, and excitation methods. The generation of a pure mode through appropriate selection of input signal and transducer configuration has been discussed. A variety of signal processing techniques from simple time domain to relatively complex two-dimensional Fourier analysis are available. Time domain processing can often be applied satisfactorily in low frequency-thickness regions where only two modes can propagate, but tends to be unreliable above the cut-off frequency of the a_1 mode. As an example of the design of a Lamb wave testing regime, a set of tests on a butt-welded steel plate with simulated weld defects of different depths is described. It was shown that by operating below the $a_1$cut-off frequency with judicious selection of testing technique, the presence of defects can be detected reliably from changes in the shape of the received waveform.

Kundu et al **[7]** studied the importance of near Lamb mode imaging of multilayered composite plates. Different Lamb modes generate various stress levels in different layers, so all lamb modes are not equally sensitive to internal defects of various layers. In this paper it is investigated how by fine-tuning the frequency and striking angle of the incident beam in the neighborhood of a Lamb mode one can separately detect internal defects in layers of mirror symmetry in the upper and lower halves of a plate. **Figure 3.1** shows the internal defects in five layers of composite plate. The incident angle and the signal frequency should be such that they are close to Lamb mode but not exactly on Lamb mode.

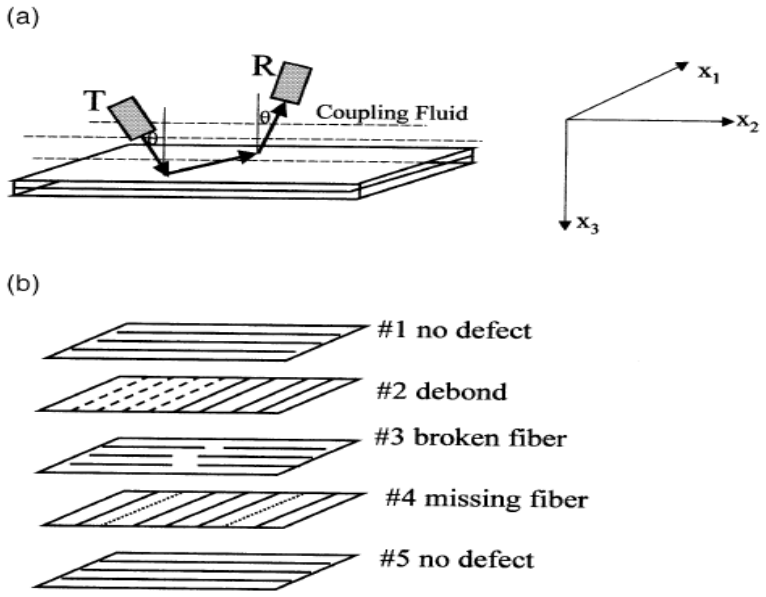


Figure 3.1: Relative orientation of transmitter, receiver and plate specimen, (b) Schematic of the internal defects in five layers of the composite plates specimen

Dalton et al [8] presented study on Ultrasonic guided waves through metallic aircraft structure using dispersion analysis and numerical modeling. An active guided wave system based on current technology must feature efficient propagation over distances of at least 1m with an attenuation of not more than about 40dB/m. Propagation was examined across free skin, tapering skin, skin loaded with sealant and paint, double skin jointed with either sealant or adhesive, and lap and stringer joints, which together adequately characterize metallic monocoque fuselage construction. Guided wave propagation through double skin features the inevitable generation of twin modes with similar phase velocity, which interact with each other during propagation. This interaction crucially determines the efficiency of propagation across narrow joints and effectively precludes propagation across a succession of joints. This work lead to the conclusion that an active aircraft system that relies on guided wave propagation of more than 1m is not feasible, whereas localized guided wave monitoring of structurally significant areas is a more practical approach.

Kessler et al [9] presented study on In-situ damage detection of composite materials using Lamb wave techniques to quasi-isotropic graphite/epoxy test specimens containing delamination, transverse ply cracks and through-holes defects. **Figure 3.2** shows the CFRP specimen. Linear wave scans were performed on narrow laminated specimens and sandwich beams with various

cores by monitoring the transmitted waves with piezoceramic sensors. The time of flight of a Lamb wave pulse between an actuator and sensor was determined. Lamb wave techniques provide the possibility of determining damage location due to their local response nature. The disadvantage of Lamb wave methods is that they require an active driving mechanism to propagate the waves, and the resulting data can be more complicated to interpret than for many other techniques. Overall however, Lamb wave methods have been found to be effective for the in situ determination of the presence and severity of damage in composite materials.

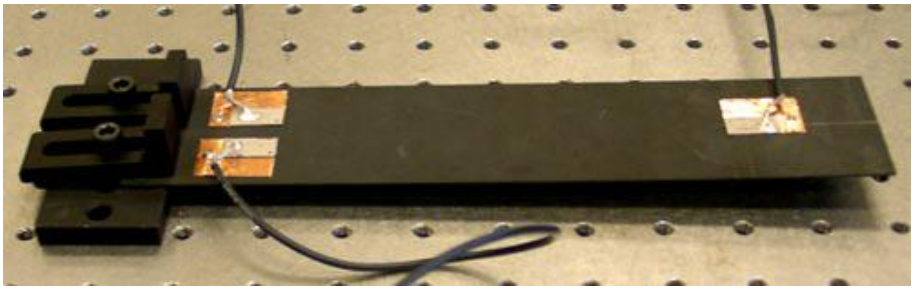
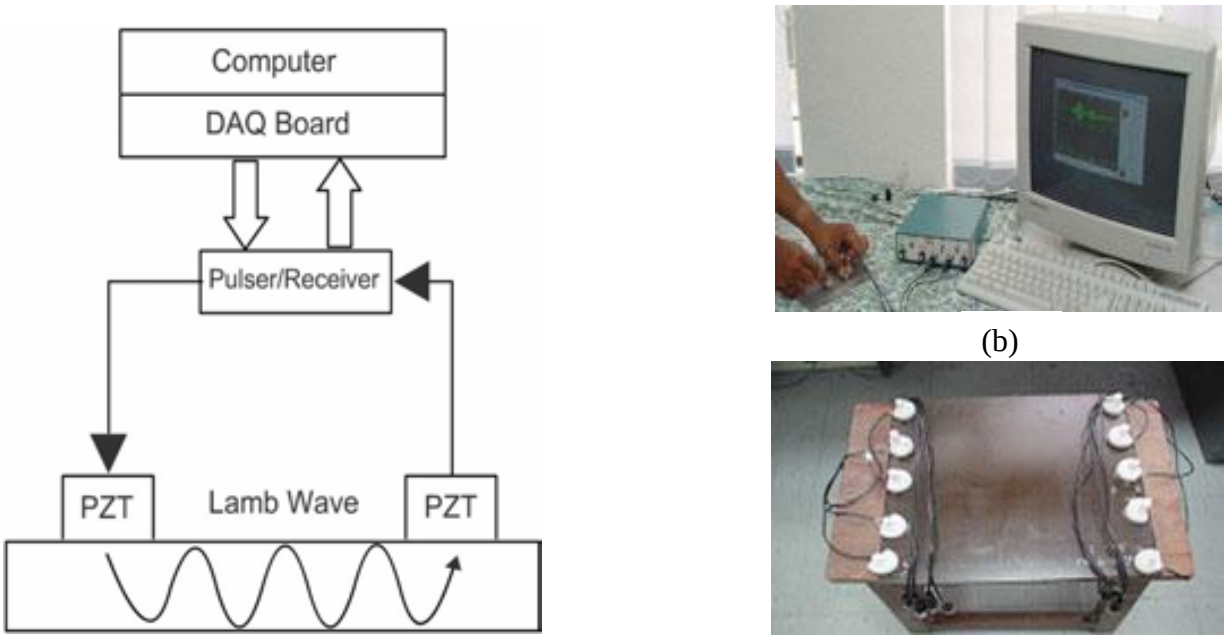


Figure 3.2: CFRP specimen (250 mm × 50 mm) with piezoceramic actuator and sensors

Prasad et al [10] presented study on structural health monitoring of composite structures using lamb wave tomography. The study presents the possibility of constructing tomograms from a network of sensors generating and sensing Lamb waves in thin, multi-layered, anisotropic composite plates. It is observed that an improved tomograms result when the anisotropic and attentive characteristics of composite plates are accounted for by using the newly identified energy of the earliest Lamb wave signals as the reconstruction parameter, also by modifying the sensor configuration from conventional geometries (and thereby also optimizing the number of sensors), and by normalizing the Lamb wave energy data of the defective sample with respect to that of the defect-free sample. Sensors were arranged in modified cross-hole configuration. The energy of the early part of the Lamb waveform is an effective parameter for tomographic reconstruction. Narrow bandwidth transducers such as PZT crystals excited by tone burst signals were found to be more suitable than commercial transducers, which had larger bandwidths. Experimental results indicate that in anisotropic composite laminates the tomogram obtained from modified cross-hole configuration (with sensors on all four sides) distinguishes the defective region better, when compared to the tomogram obtained from the regular cross-hole configuration. **Figure 3.3** shows the schematic diagram of the experimental setup. Tomogram of

cross-ply laminate with one defect and tomogram of quasi-isotropic laminate with two defects have been shown in **Figure 3.4** and **Figure 3.5** respectively.



(a) (b) (c)

Figure 3.3: Experimental setup (a) Schematic, (b) instrumentation and (c) 5 × 5 cross-hole setup.

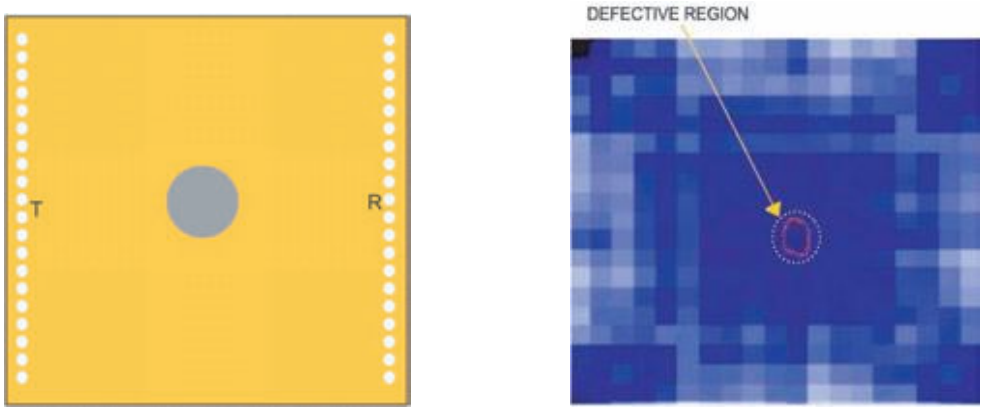


Figure 3.4: Tomogram of cross-ply laminate with one defect.

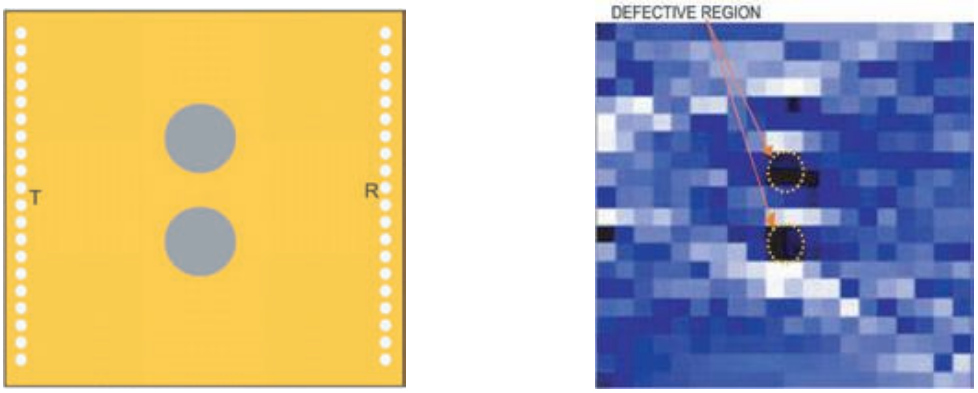


Figure 3.5: Tomogram of quasi-isotropic laminate with two defects.

Edalati et al [11] presented study on defect evaluation in thin Aluminum plates using lamb waves. Two ultrasonic lamb wave techniques, pulse-echo (a1 mode) and emission (s1 mode) were used for interpretation of notch defects with depth of 10%, 30% and 60% of plate thickness (shown in **Figure 3.6**). Frequency of transducer was 2 MHz. It was found that amplitude analysis can give some qualitative and quantitative information about defects depth. **Figure 3.8** shows the waveforms of ultrasonic lamb wave in pulse-echo technique and **Figure 3.9** shows the waveforms of ultrasonic lamb wave in emission technique. Amplitude analysis showed that defect depth could be evaluated by drawing the DAC curves (**Figure 3.10**). Pulse echo was more sensitive for defect detection than emission technique. Location of defects was found by assessment the group velocity in pulse echo technique and the length of defect was determined by the law of 6 dB drop.

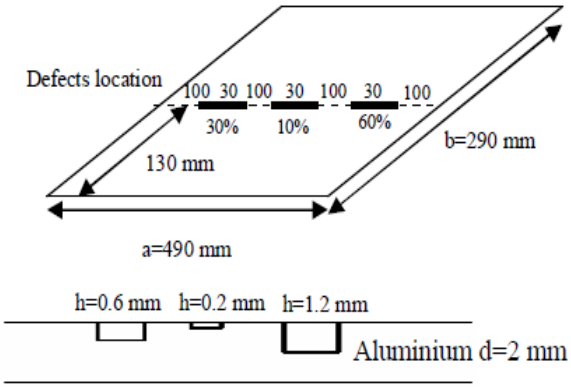


Figure 3.6: The schematic mapping of fabricated Aluminium plate.

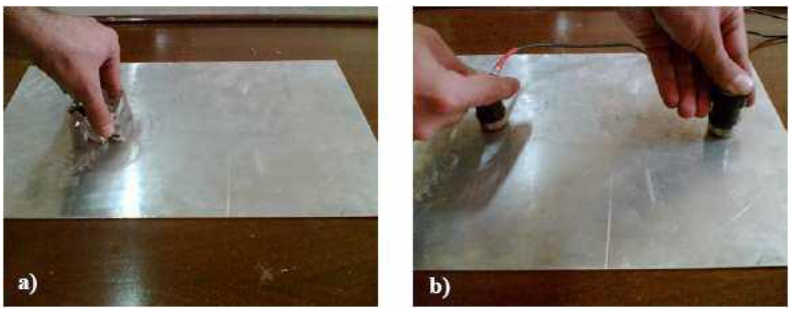


Figure 3.7: The lamb wave testing methods: a) pulse-echo technique and b) emission method

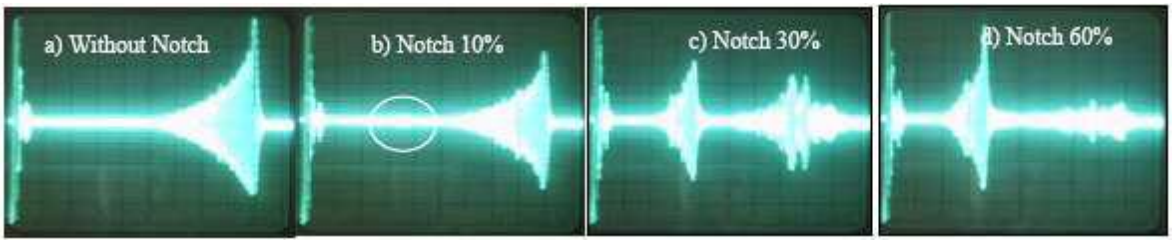


Figure 3.8: The waveforms of ultrasonic lamb wave in pulse-echo technique, a1 mode evaluated (defect to probe distance was 75 mm)

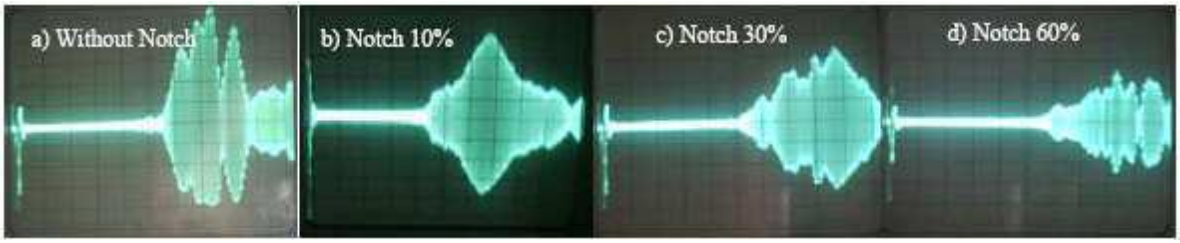


Figure 3.9: The waveforms of ultrasonic lamb wave in emission technique, s1 mode evaluated (defect to transmitter distance and defect to receiver distance was 50 mm)

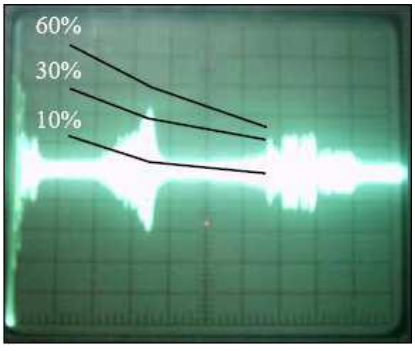


Figure 3.10: The Drawing the DAC curve for defect evaluating by assessment the notch defects with the depth of 10%, 30% and 60% as reference defects.

Demcenko et al [12] discussed the application possibilities of air-coupled ultrasonic technique for investigation of the Lamb wave propagation in the composite material and the numerical simulations of the Lamb wave interaction with the delamination type defect were presented. The Lamb wave velocities were measured in delaminated and defect-free areas of the composite material GLARE. The structure of the GLARE composite is shown in **Figure 3.11**. The delamination position influence on the Lamb wave propagation velocity is investigated experimentally and numerically. He concluded that he air-coupled ultrasonic measurement technique can be used for accurate investigation and testing of various types of the materials, but it is not suitable for the fundamental investigations of the waves interactions with the non-homogeneities or defects in the structures.

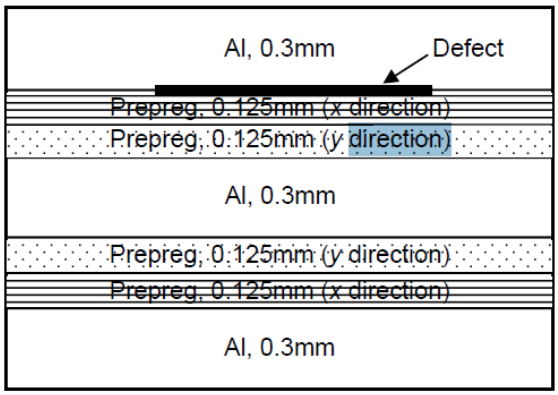
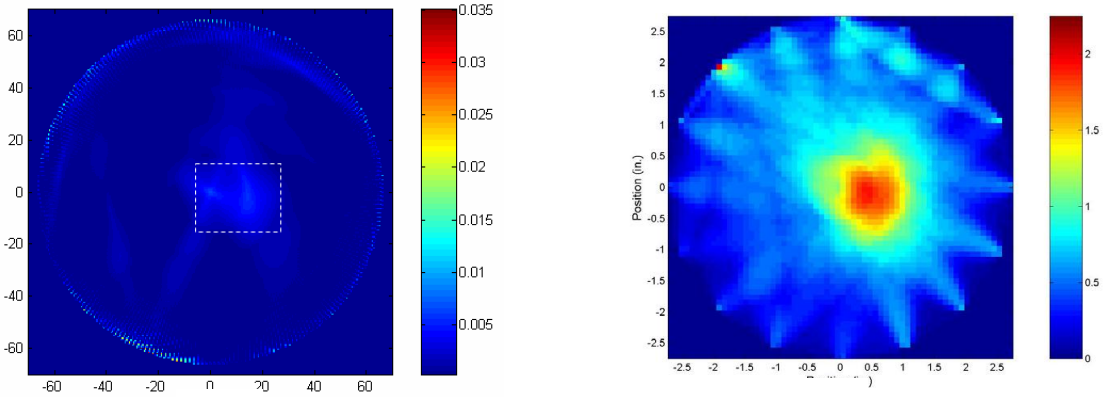


Figure 3.11: The structure of the GLARE3-3/2 composite and the position of the defect.

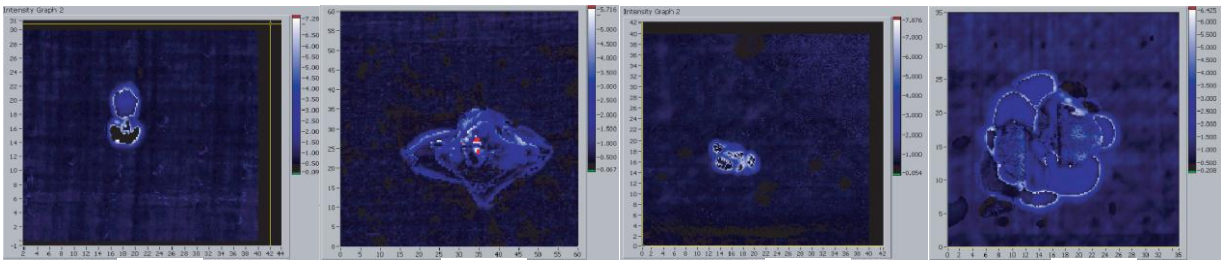
Hay et al [13] demonstrates the capability of technology to detect material loss on real aircraft components using embedded piezoelectric sensors on hidden surfaces. Firstly, it demonstrates that Lamb wave ultrasonic tomography can be used to accurately map material loss on an exposed aircraft surface with sensors embedded on the structure's hidden surface. Secondly, it compares tomographic images generated by fan-beam back projection and the signal difference coefficient methods, showing clearly that the latter are more sensitive to material loss. In filtered back-projection and algebraic CT, the reconstruction feature is assumed to be a line integral of the material properties in the direct path connecting the transmitter and the receiver. It is more suitable for gradual change of material properties. **Figure 3.12** shows the tomographic images obtained by different techniques.



(a) (b)

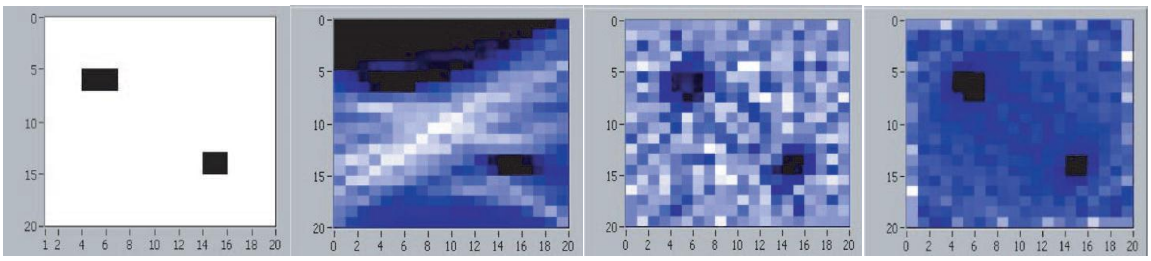
Figure 3.12: Reconstructed tomographic image obtained with different techniques.

Balasubramaniam et al [14] presented study on SHM of thin multi-layered graphite fibre reinforced composite plate. Low velocity impact damages (6-12J) were introduced by the drop weight method in cross ply and quasi isotropic lay-ups. Impact damages were the primary source of delamination and fibre cracking in composite structures. Damage assessment was carried out by conventional C-scans and ultrasonic Lamb wave tomography. **Figure 3.13** shows the Ultrasonic C-scan of impact damages at the maximum damage ply. Ultrasonic Lamb waves were generated and received with PZT crystals in an MCH configuration. Lamb wave based tomography based on modified cross-hole sensor configuration was used to image the damage as a function of impact energy. **Figure 3.14** shows the Tomographic reconstruction of an anisotropic medium with cross-hole, modified cross-hole and compensated cross-hole configuration.



(a) (b) (c) (d)

Figure 3.13: Ultrasonic C-scan of impact damages at the maximum damage ply: (a) 7 J on CPLT (b) 11 J on CPLT, (c) 8 J on QILT; and (d) 11 J on QILT.



(a) (b) (c) (d)

Figure 3.14: Tomographic reconstruction of an anisotropic medium with simulated projection data: (a) schematic of the defective medium (b) with cross-hole configuration, (c) with modified cross-hole configuration, (d) Compensated modified cross-hole.

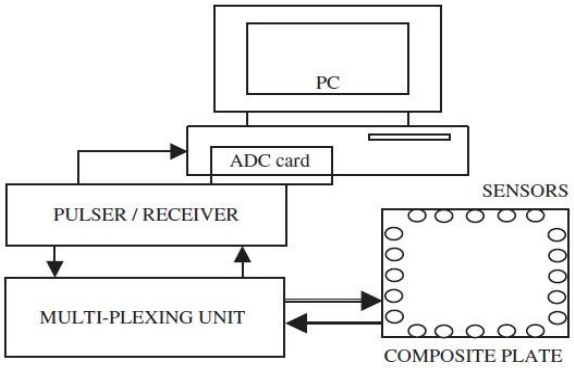


Figure 3.15: Schematic diagram for Lamb wave tomography.

Wood and Loveday [15] used guided wave for the inspection of cracks in glass fibre reinforced composites rods. Specially developed waveguide finite elements are used to determine the wave propagation characteristics of the rod. Conventional transient finite element modeling is performed in order to determine what effects cracks have on the passage of the induced waves, and therefore also on the eventual output signals. This has furnished the frequency dependence of the wave propagation in the rods, which has enabled the selection of an appropriate mode of excitation for practical testing. Additionally, the guided wave analysis allows for a better interpretation of measured signals, since modal velocities and dispersion characteristics are predicted. The presence of damage results in reflected signals and changes in the transmitted signals, both of which are quantifiable in terms of reflection and transmission coefficients. It has been shown that these coefficients can be defined and recorded in different ways, but they can be

used to quantify the extent of damage present in a sample, relative to undamaged samples. The block diagram of the experimental setup is shown in **Figure 3.16.**

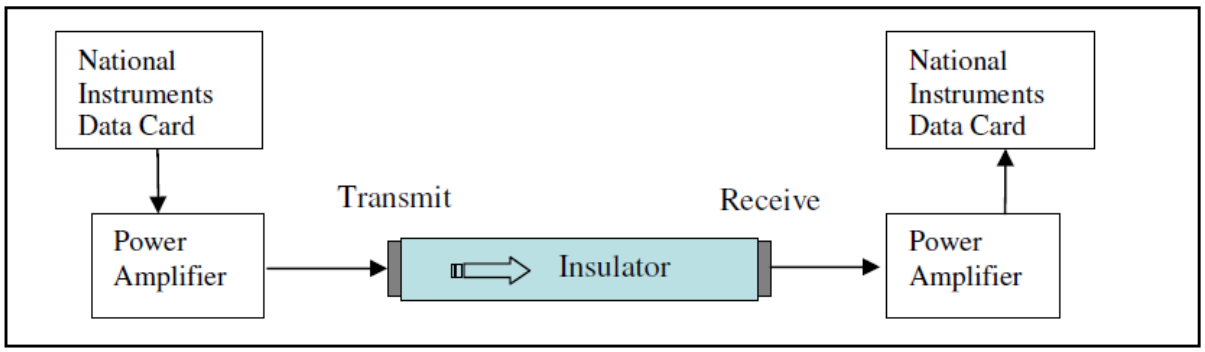


Figure 3.16: Experimental setup

Kumar et al [16] Presented study on In-situ damage detection in fibre reinforced polymer composites plates using piezoelectric wafer active sensor (PWAS) and non-contact laser Doppler velocimeter. PWAS were embedded in the middle layer of composite laminate (Glass-Epoxy [45°/-4570°/90°]s) prepared by hand lay-up as shown in **Figure 3.17**. The signal transmission and reception between the sensors were studied. A laser vibrometer (Polytec OFV-5000) was also used to ensure working condition of the sensors in the structure by pointing it on the surface of the sensor and at a point away from the sensor. Low Velocity Impact damage simulated in the laminate using drop-weights was monitored by observing the signal transmission among the sensors and with Laser vibrometer. The effect of embedding the sensors on the strength of the structure was studied. A marginal reduction in the strength was observed for the laminates with embedded sensors.

Figure 3.17: Experimental set for Laser based measurements for Lamb wave response on glass-epoxy composite samples with PWAS as embedded sensors.

Raisutis et al [17] Ultrasonic air-coupled technique using guided waves has been selected for inspection of wind turbine blades, because only one side access is enough and no contact is needed. Dispersion curves of phase velocities as well as leakage losses versus frequency were calculated using numerical global matrix model. Taking into account the results of the performed simulations the frequency of the ultrasonic transducers was selected to be 290 kHz due to non-dispersive region of phase velocities. The ultrasonic air-coupled technique using guided waves was used for investigation of the artificial internal defects in the wind turbine blade. These defects (diameter 19 mm and 49 mm) were made on the internal side of the main spar (shown in **Figure 3.19 (a))**. From the ultrasonically obtained images it is possible to recognize the geometry of defects and to estimate approximate dimensions of the defects as shown in **Figure 3.19**. From the simulation results it can be seen that for ultrasonic NDT investigations of wind turbine blades fundamental *A*0 mode should be used due to low leakage losses and less dispersive region at the frequencies higher than 290 kHz.

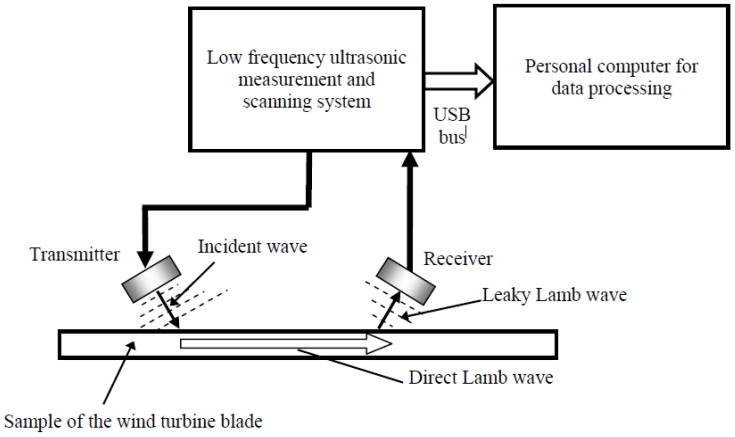
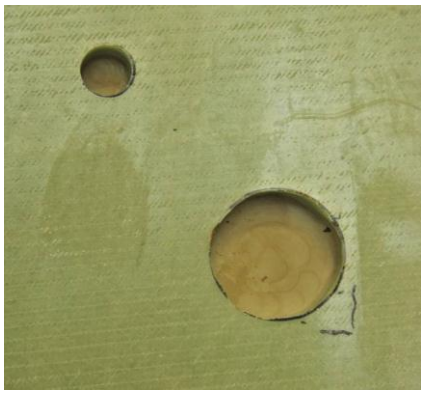
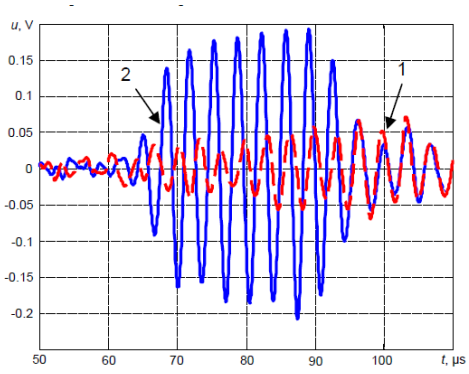


Figure 3.18: Schematic of air-coupled ultrasonic technique



(a)



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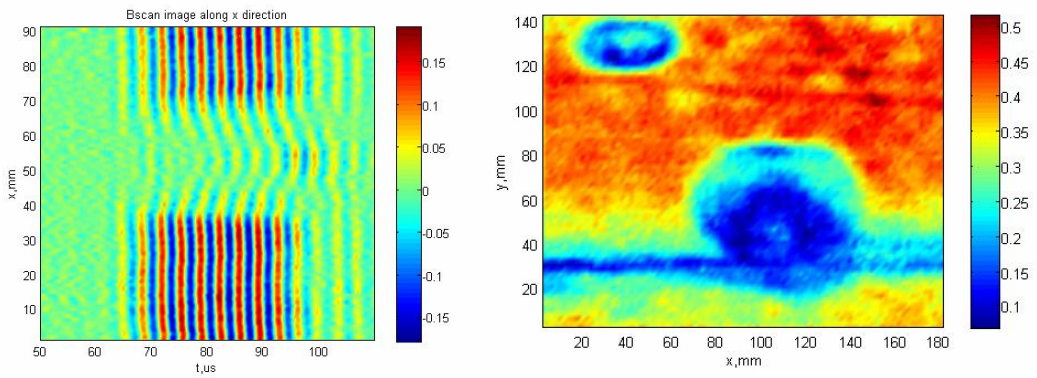


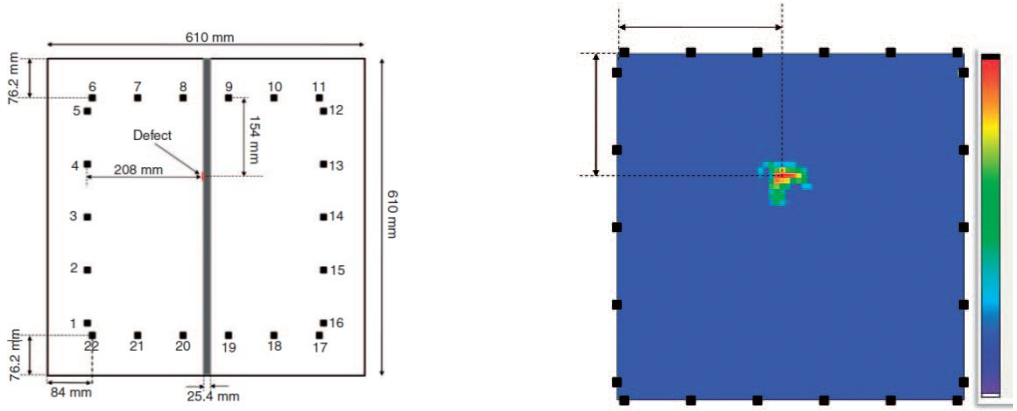
(c) (d)

Figure 3.19: Wind turbine blade (a) with artificially made defects (b) A-scan (c) B-scan (d) C-scan.

Yong et al [18] an application for Lamb Waves Tomography (LWT) was presented using time-frequency analysis. By the interaction of Lamb wave and defects, there would be several modes, which were likely to result in the overlap of echoes in time domain. Based on wavelet transform, in this paper, arrival time of the Lamb waves was extracted accurately in time-frequency domain, and this method facilitated to get wave arrival time of wave energy easier and more accurate than others before. Wavelet transform was a better way to incorporate time-frequency analysis into tomography algorithms in order to improve image quality. It was found that the WT using the Gabor wavelet was an effective tool for analyzing the time-frequency behaviour of Lamb wave. The time delay needed in Lamb wave tomography could be determined from the properties of the peak of the magnitude of WT in the time-frequency distribution.

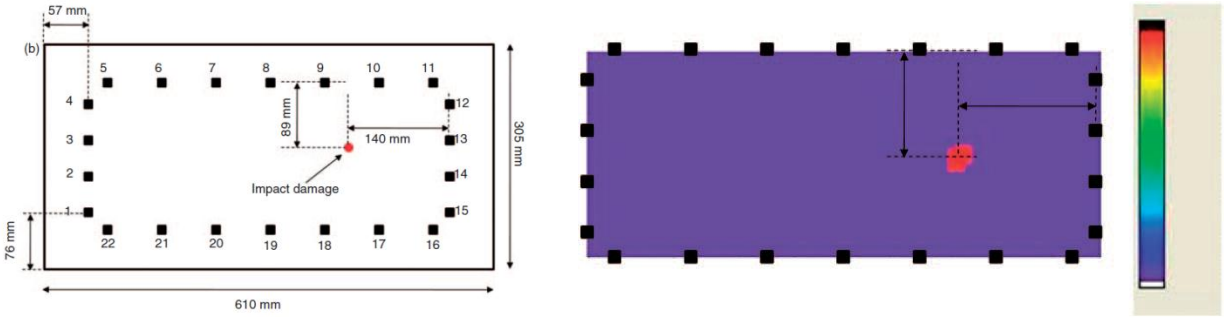
Yan et al [19] presented study on structural health monitoring (SHM) using ultrasonic guided wave imaging techniques. Two imaging approaches of utilizing guided wave leave-in-place sensors for early detection of defects in plate-like structures were studied. The first approach was based on a guided wave tomographic technique, in which the region surrounded by a sparse sensor array was monitored. The second one was a phased array approach, in which sensors were attached to a structure in a compact format to form an array. The region subjected to inspection and monitoring was the region outside the array. Both techniques have shown excellent capability of determining damage size, location, and severity. The guided wave tomography technique was proven to be capable of handling complex structures. Excellent sensitivity to the presence of defects was achieved. **Figure 3.20** shows the tomogram generated by the SDC

(signal different coefficients) based RAPID (reconstruction algorithm for probabilistic inspection of damage) technique for the machined defect in the welded plate. The defect was well defected in the tomogram. The location of the detected defect agrees with the actual defect location very well. **Figure 3.21** shows the experimental setup of a tomography test on a woven composite plate. The damage was well detected. Due to the material anisotropy, the indication of damage appears slightly off from the actual damage location.



(a) (b)

Figure 3.20: (a) Geometry of the welded plate showing sensors and defects, (b) The tomogram generated by the SDC-based RAPID technique.



(a) (b)

Figure 3.21: (a) Woven composite plate showing sensors and defects, (b) Tomogram of the impact damage in the composite plate.

Alexopoulos et al [23] presented study on polyvinyl alcohol-carbon nanotube (PVA-CNT) fibre embedded in glass fibre reinforced plastic composites which were used as a strain sensor for the damage monitoring of the composites. Sensing was made by the in situ measurement of the electrical resistance of the embedded PVA–CNT fibre during the mechanical tests. The multi-

functional materials were tested in tensile progressive damage accumulation (PDA) tests. These tests aimed to seek the electrical response of untreated and pre-stretched PVA–CNT fibres with known level of progressively induced damage to the composite. PVA-CNT fibre electrical resistance readings are directly correlated to induced damage. Cyclic loading of the composites led to the conclusions that pre stretching of the PVA-CNT fibres is resulting to a fairly linear behavior of the fibre as a function of strain. Disadvantage of this fibre is that the correlation between resistance and strain of the fibre alters with induced damage.

Saponara et al [24] presented study on structure health monitoring of glass/epoxy composites plates using PZT-4 ceramic and single crystal PMN-PT transducers specimens were manufactured with a delamination starter located in the middle of the plate, and were subjected to axial tensile fatigue at a high stress ratio. Both the transducers were positioned on each side of the delamination starter. An assessment of the transducers sensitivity and performance was made, Results indicate that the PMN-PT transducers may be more resilient to fatigue damage of the host structure and possibly generate less dispersive Lamb waves. However, these aspects are compounded with higher costs and manufacturing difficulties.

3.1 Gaps in literature review

Following gaps were found in literature review:-

1. Damage detection with tomography for GFRP plates is still an area need to be explored properly.
2. Limited work has been employed for damage detection in thin laminate composite using ultrasonic guided waves.
3. Suitable modes and frequency for different damages like delamination, missing fibre, matrix cracking, fibre breakage etc. need to be investigated.

CHAPTER 4:
EXPERIMENTAL DETAILS

4.1 Introduction

This chapter discusses the method of fabrication of Glass fibre laminates, size/dimensions of the samples made and the experimental setup required to carry out for the proposed work.

4.2 Fabrication of Glass Fibre Laminates

For the manufacturing of GFRP laminates following material has been procured from BASF construction chemicals (India) private limited.

- E-Glass 900 gsm unidirectional glass fibre sheet roll (width 50 cm) shown in **Figure 4.1.**
- MBrace Epoxy & hardener shown in **Figure 4.2.**

Figure 4.1: Glass Fibre roll

Figure 4.2: Base and Hardener

Glass fibres are made of silicon oxide with addition of small amounts of other oxides. In the study E-glass was used which has good electrical properties. The specimens were prepared by hand lay-up method (discussed in chapter 2).Glass fibre should not be touched with bare hand as its direct contact with skin transfers some of its tiny particles into the body. Therefore it should be handled by wearing the gloves. Following steps were used for the manufacturing of GFRP laminates.

Step 1: Cutting of Glass fibre

As discussed earlier Glass fibre sheet is available in rolls of width 50 cm. The first step is to cut the glass fibre sheet as per the required dimensions as shown in **Figure 4.3**. The sheets were initially cut 50-60 mm more than actual sample length. The reason for overcutting was that after laminated specimen has been fabricated & cured, extra edges need to be trimmed in order to remove flaws after layup operation. Glass fibre sheet can be cut with the help of normal scissor.

Figure 4.3: Cutting of glass fibre

Step 2: Mixing of Base and Hardener

The GFRP sheets have been epoxy coated in order to make a composite material laminate.

Epoxy resin basically consists of two parts.

- **Base:** Base is highly viscous blue liquid which is considered as the main ingredient.
- **Hardener:** Hardener is orange colored liquid which is added to the base to help it in settling down by starting the exothermic reactions.

Base and Hardener is mixed in the ratio of 5:2 (by weight) respectively. While mixing, the hardener should be added into the base in small quantities and mixed thoroughly step by step respectively as shown in **Figure 4.5.** If mixing is not done properly, the material does not settle well. Also if the ratio of the hardener is more than the required quantity then the life of the specimen is observed to effect adversely. It is important to mention that the prepared amount epoxy resin should be consumed within 20 minutes otherwise it hardens up in the container itself. Approximately 100 gms of epoxy is required to apply on one side of 35 X 25 cm^2 sheet.

Figure 4.4: Pouring base into the container

Figure 4.5: Mixing of base and hardener

Step 3: Applying epoxy on fibre

After the epoxy is prepared by through mixing of base and hardener, it is applied on the Glass fibre sheet with the help of steel scrapper evenly on all sides of the sheet as shown in **Figure 4.6.** Epoxy should be applied on the sheet in such a way that no air bubble is entrapped in it otherwise it can lead to the manufacturing defect and also affects the ultrasonic signal. To manufacture two ply laminate, two glass fibre sheets with epoxy coated are made and placed over one another with 0 degree orientation (i.e. fibre in the same direction) and epoxy is applied between them. Finally prepared laminate specimen consists of three epoxy layers & two glass fibre sheets in between them as shown in **Figure 4.7.**

Figure 4.6: Applying epoxy on the glass fibre sheet

Figure 4.7: Front view of the specimen

Step 4: Cutting the extra edges of the laminate

The specimen is left for curing at ambient temperature for 12 hours after applying the epoxy coat. After curing the specimens are cut to required size using the hand saw or circular saw machine. Cutting of GFRP laminate should be done very carefully as while cutting tiny particles from specimen can enter into the body through skin or can be inhaled which are not good for health. If circular saw machine has been used for cutting the plates, make sure that the mouth should be properly covered as while cutting the tiny particles get mixed in the surrounding air and there are chances of their inhaling.

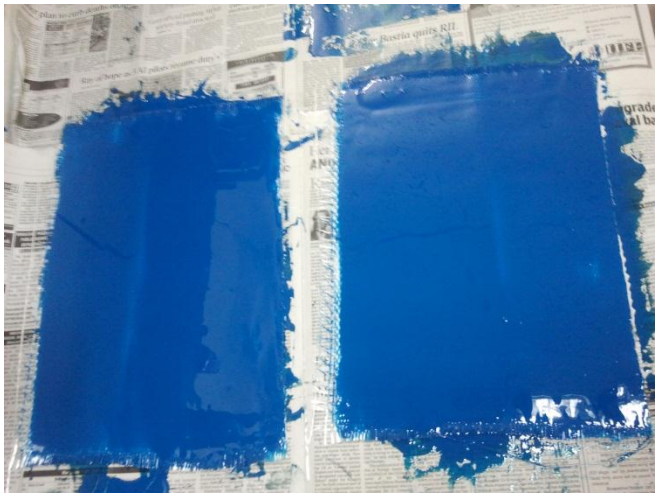


Figure 4.8: Specimens after applying epoxy

4.3 Specification and method of fabrication of the defected specimen

The study has been carried out for three defects namely notch, missing fibre and delamination. These defects were artificially induced in the specimens. Method of inducing the artificial defects and specification of the specimens has been discussed as below.

4.3.1 Specimens with Notch defect:

Notches are kind of external damage that may appear on a GFRP laminate during its service life due to abrasion or wear by another material. The study of notch has been divided into two categories according to the orientation of the notch with the fibre.

- **Method of Fabrication:** For studying the notch defect healthy specimen has been prepared as discussed above in **section 4.2.** Notch can be cut with the help of hack saw blade or saw. The study has been divided into four categories. Firstly the healthy specimen has been tested with ultrasonic guided waves and its signature is set as reference signature and subsequently a notch defect is inflicted on the specimen with the help of saw blade. Depth of notch is increased to three layers of the laminate.
- **Specification/Dimension:**

Specimen 1: Notch defect in the direction perpendicular to the fibre.

In this study, the orientation of the notch is across the fibre direction. The dimensions of the specimen are 300 x 120 x 4 (approx.) mm^3.

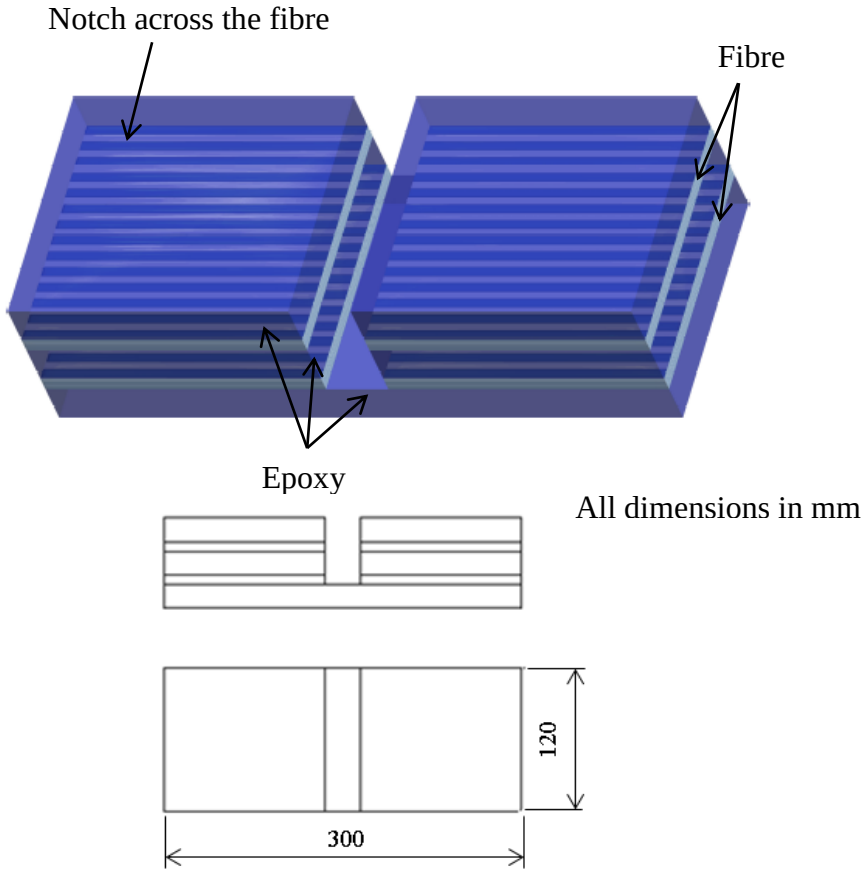


Figure 4.9: Specimen 1 for notch defect

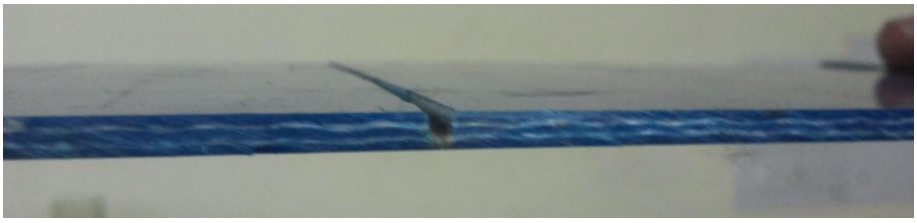


Figure 4.10: Notch defect

Specimen 2: Notch in the direction of the fibre.

In this study, the orientation of the notch is across the fibre direction. The dimensions of the specimen are taken as 300 x 120 x 4 mm^3.

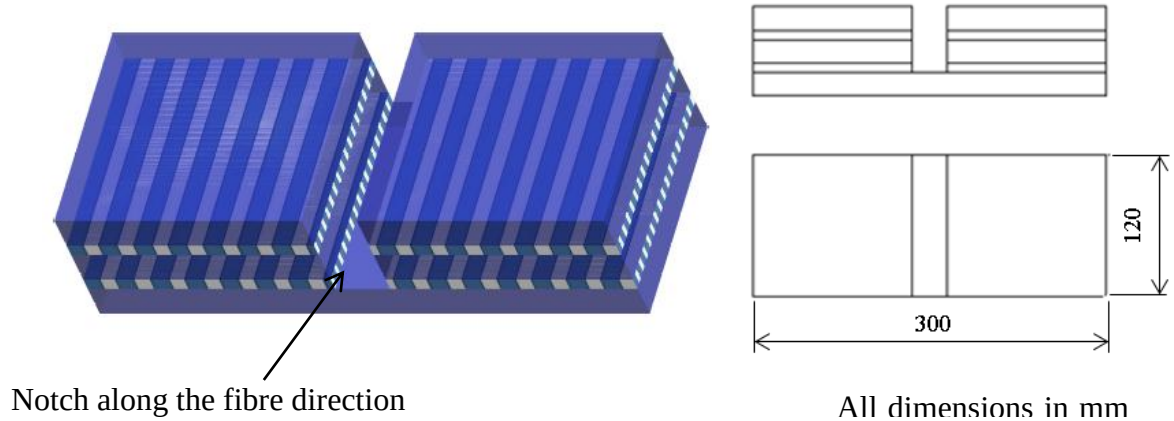


Figure 4.11: Specimen 2 for notch defect

4.3.1 Specimens with Missing Fibre defect

As the name suggested missing fibre is the defect when there is absence of fibre from the laminate. It is the type of internal defect.

- **Method of fabrication:** For inducing the missing fibre defect, there are some changes in the fabrication procedure as discussed in **section 4.2** for preparing the healthy laminate. For inducing the missing fibre defect cello tape of required shape and dimension is pasted at the desired location on the fibre sheet before applying the epoxy. When one side of the laminate has been cured, portion of the fibre on which the cello tape was applied is cut from the other side of the laminate on which epoxy has not been applied as shown in **Figure 4.12**. The rest of the procedure for the fabrication of two ply laminate is same as discussed in **section 4.2**. The fibre has been cut from the one of the layer of the two ply laminate. To carry out the study for varying depth the laminate has been studied from the

either side. From one side missing fibre was there in second layer and from other side it was in fourth layer.

- **Specification/ Dimension:**

  Specimen 1: For Varying Depth

  The dimensions of the specimen are 280 x 180 x 4 (approx.) mm^3.

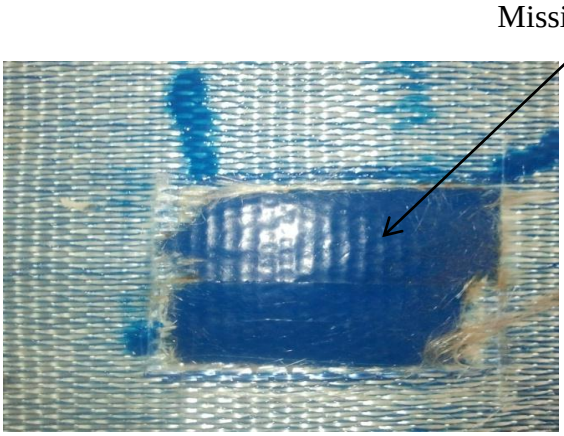


Figure 4.12: Removed portion of the fibre

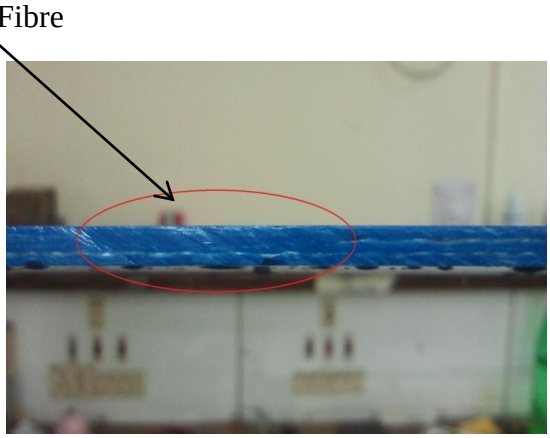


Figure 4.13: Missing fibre defect

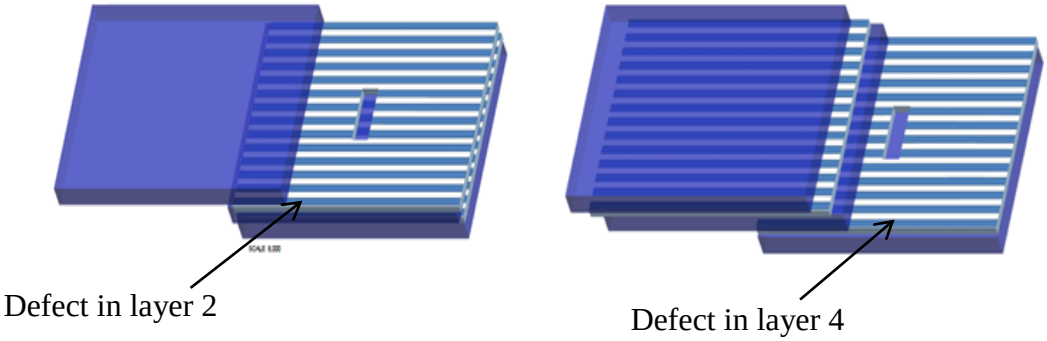


Figure 4.14: Specimen for missing fibre defect of varying depth (a) layer 2 (b) layer 4 (c) Orthographic view

Specimen 2: Missing fibre of varying length

The dimensions of the specimen are 300 x 270 x 4 (approx.) mm^3. In this study the width of the missing fibre has been varied in two steps of 50 mm to 25 mm as shown in **Figure 4.15.**

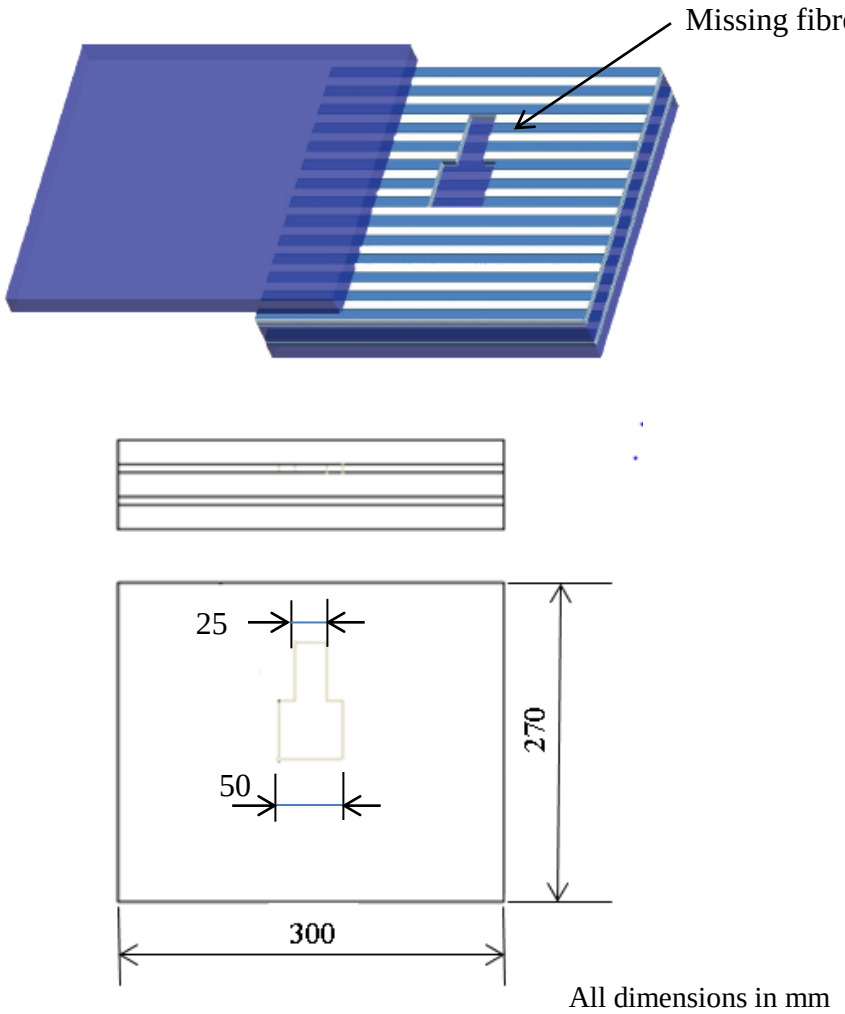


Figure 4.15: Orthographic views of specimen for missing fibre of varying length

4.3.2 Specimen for Delamination

Delamination is the defect in which the plies of the laminate get separated from each other and this separation is commonly caused by bad manufacturing, impact damage or aging.

- **Method of fabrication:** For the study, delamination defect was artificially induced in the specimen. Two ply laminate was used to carry out the study for delamination defect and the delamination was induced between two glass fibre sheets i.e. between second and the fourth layer. Two glass fibre sheets with one side epoxy coated were fabricated with the method as discussed above. Then aluminium strip was placed between the two laminates

where delamination was required while applying the epoxy between them. Some oil was applied on the surface of the aluminium strip to avoid bonding with the epoxy. After the laminate has been cured that aluminium strip was removed to cause delamination.

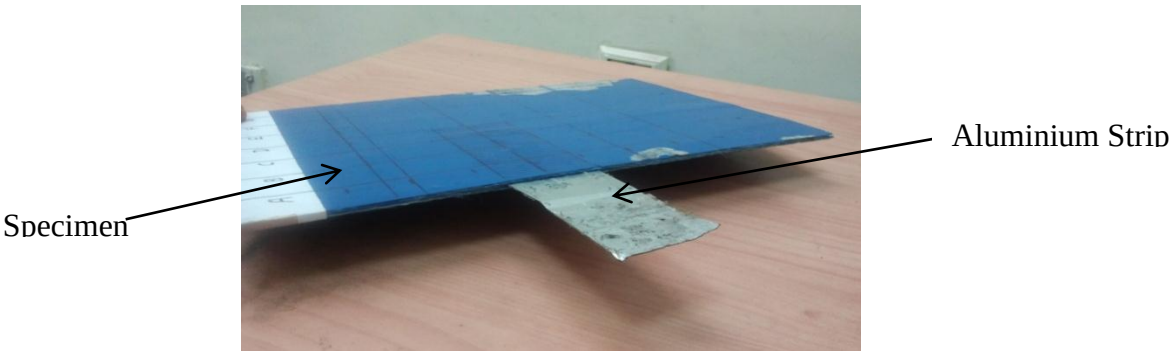


Figure 4.16: Aluminium strip placed inside the laminate

- **Specification/Dimensions:**

  Specimen 1: Delamination of constant length

  The dimensions of the specimen are 300 x 200 x 4 mm^3. In this study the extent of the delamination has been constant of width 40 mm.

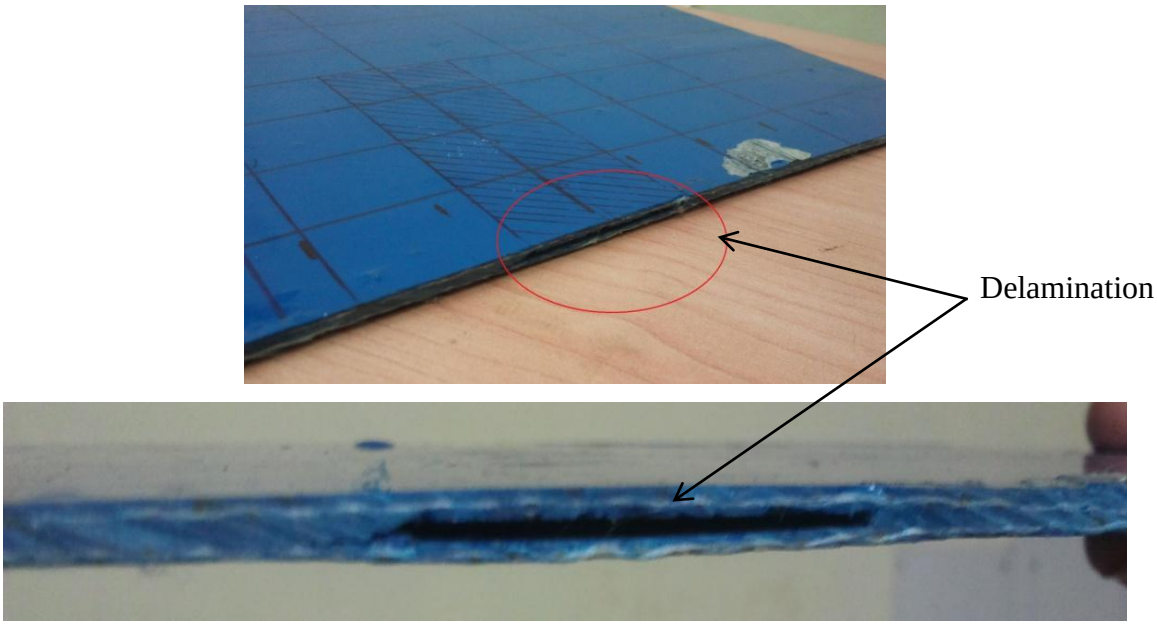
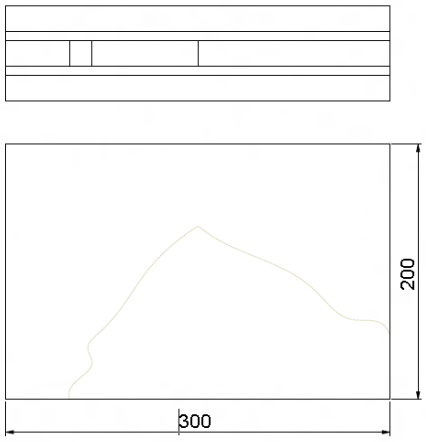


Figure 4.17: Delamination

Specimen 2: Uneven Delamination

The dimensions of the specimen are 300 x 200 x 4



All dimensions in mm

Figure 4.18: Orthographic views of specimen for uneven delamination

4.4 Experimental setup

The experimental setup required to carry out the study for ultrasonic testing are:

1. Transducer
2. Pulser/receiver system
3. Digitizer card (in computer system)
4. Four axis scanning setup
5. Water tank

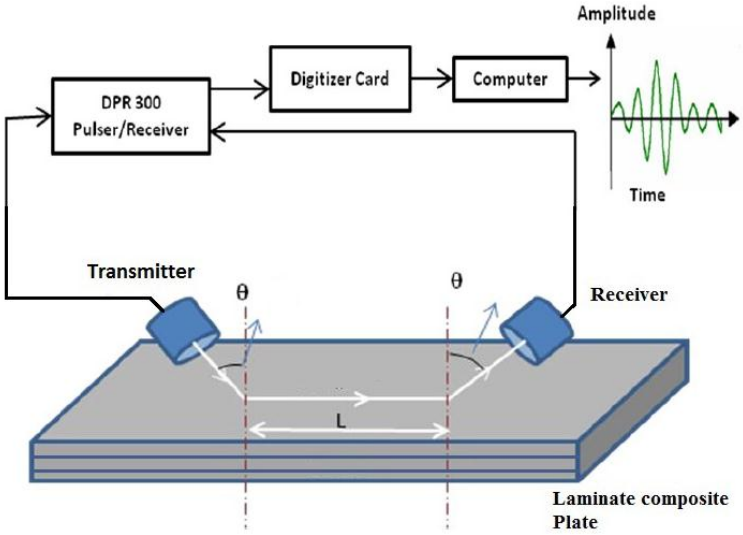


Figure 4.19: Ultrasonic experimental setup for testing in water

In this study the testing of GFRP laminate plate has been done in water as it acts as a better couplant as compared to air. The experimental setup consists of pulser/receiver system which generates the pulses. This is sent to the transducer which converts the electrical pulse to mechanical pulse. Transmitting transducer is kept in contact with the composite plate using the couplant (water) and at the other end the receiving transducer is arranged in the same way. This transducer is connected back to the pulser/receiver, sends the signals to the digitizer card which is connected to computer hardware. The equipments used in this study have been discussed below.

1. **Transducer:** It is a single element longitudinal wave transducer. It can be used in straight beam flaw detection and thickness gauging, detection and sizing of delamination, material characterization and sound velocity measurements. OLYMPUS PANAMETRICS Standard transducer of 0.5 MHz (1"diameter) shown in **Figure 4.2**. It is an immersion type transducer.

Figure 4.20: Immersion probes (0.5 MHz)

2. **JSR Ultrasonics DPR 300 Pulser/ Receiver System:** DPR300 pulser produces a high voltage electrical excitation pulse and applies this pulse to the instrument's T/R connector. An ultrasonic transducer connected to the T/R connector via a length of 50Ω coaxial cable is then employed to convert the electrical energy of the excitation pulse into an ultrasonic pulse that is propagated into a test material or medium. With the DPR300 configured for pulse-echo mode operation, acoustic echoes reflected from interfaces or defects within the test material are converted by the transducer into electrical signals that are presented to the T/R connector of the DPR300. The low-noise DPR300 receiver amplifies these electrical signals, and the signals then pass through adjustable high pass

and low pass filters. The DPR300 receiver gain is adjustable between -13 dB and 66 dB, and there are six high pass and six low pass filter settings for band-limiting the receiver frequency response. The amplified and filtered signals are available on the instrument's Receiver Output connector. The DPR300 may also be used in transmission mode operation wherein a separate receiving transducer is used to detect acoustic pulses that have propagated through a test material or medium.

Figure 4.21: JSR pulse generator

PRF Oscillator & Pulser Trigger control The internal PRF oscillator generates repetitive trigger pulses for the pulser subsystem under the control of the PRF control. Pulser Trigger control selects between the internal PRF oscillator and an external source applied to the Trig/Sync connector as trigger sources for the DPR 300 Pulser.

Pulser (Impedance/Energy/Damping): The pulser generates an excitation pulse upon receiving a trigger event from a selected source. There are four energy and two impedance values, and the single Energy and impedance control adjusts the pulse energy and the pulser impedance.

Receiver amplifier: It controls the amplification or attenuation of signals processed by the DPR300 receiver. The receiver gain can be varied from -13dB to 66 dB.

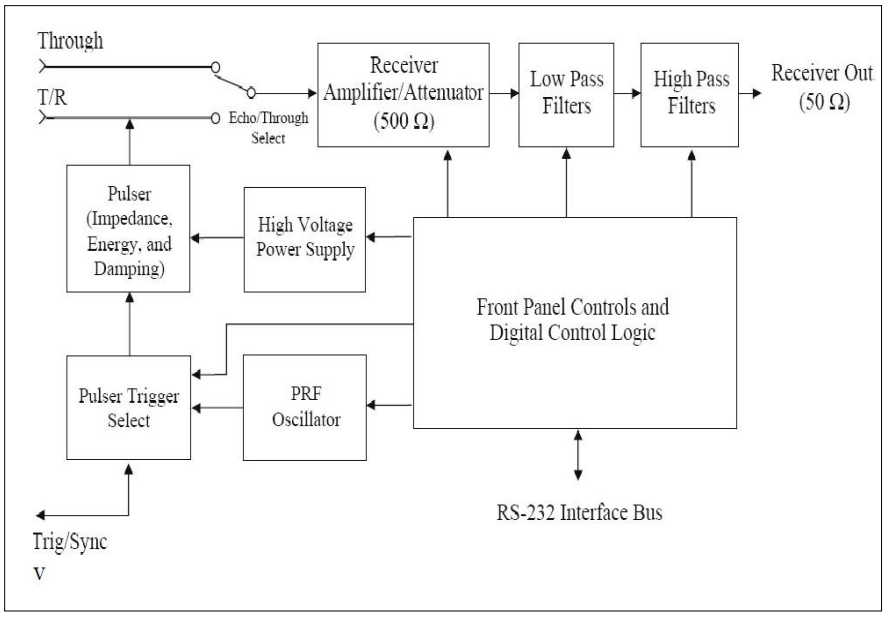


Figure 4.22: Layout of JSR Pulse Generator

Low Pass and High Pass filters: Low filters are available for reducing the bandwidth of the DPR300 receiver. High Pass filters are available for eliminating undesirable low frequency energy from the DPR300 receiver signal. High pass filtering can be used as a means of providing faster receiver recovery from strong signals such as the excitation pulse or strong interface echoes.

Pulser	
Pulse type	Negative Spike Pulse
High Voltage Supply	100V to 475V
Initial Transition (Fall Time)	<5 ns (10-90%) typical for 475V pulsers
Pulse Amplitude	-475V peak. Amplitude depends on Energy, Impedance, Damping control settings, and pulser type
Pulse Energy	1.55 µJoules minimum, 304 µjoules maximum for 475V pulsers. Dependent upon energy and voltage setting
Pulse Duration	Typically 10-70 ns FWHM for 50 load. Function of the Energy, Impedance, and Damping controls
Damping	16 Damping values: 331, 198, 142, 110, 92, 77, 67, 59, 52, 47, 43, 39, 37, 34, 32, and 30 Ω.

Mode	Pulse-echo or through transmission
Through Mode Isolation	Typically 80 dB at 10 MHz
Pulser Repetition rate	Internal: 100 Hz -5 kHz for 475V pulsers. External: 0 -5 kHz for 475V pulsers.
Sync Output	Maximum +5 V, tr< 30 ns, tw = 50 ns. min. TTL and CMOS compatible. Minimum value of load impedance is 50
Pulser Trigger Source	Selectable by computer between internal oscillator and external source
External Trigger Input	3 -5 V positive going pulse. Triggering will occur synchronously with leading edge of trigger signal. TTL and CMOS compatible
Receiver	
Gain	-13 to 66 dB in 1 dB steps controlled by the host computer
Phase	0° (non-inverting)
Input Impedance	500(through transmission)
Gain	-13 to 66 dB in 1 dB steps controlled by the host computer
Bandwidth	.001-35 MHz (-3 dB) or .001-50 MHz
High Pass Filter	DC,1, 2.5, 5, 7.5 and 12.5 MHz
Low Pass Filter	3,7.5,10,15,22.5 (35 MHz BW) or 5,10,15,22.5,35 (50 MHz BW)
Receiver Noise	Typically 49 μVpk-pk input referred(measured at 60dB,35 MHz bandwidth)
Output Impedance	50
Output Voltage	± 0.5 V into 50
Bandwidth	.001-35 MHz (-3 dB) or .001-50 MHz

Table 4.1: Specification of JSR Pulse Generator

3. **Dual-Channel High-Resolution Waveform Digitizer Model:** DC438 Dual-channel, 12-bit, 100 MHz, 200 MS/s, 4 M point acquisition memory card was used to capture the waveform. Waveforms are transferred directly into the digitizer large acquisition memories so that complex signals can be stored over very long time periods. Large memories are essential for maintaining fast sampling rates and therefore timing resolution.

Model DC438	
Bandwidth (-3 dB)	DC to 100 MHz
Full Scale Range (FSR)	250 mV, 500 mV, 1 V, 2 V, 5 V and 10 V
Impedance	50 92± 1% @ DC
Connector	BNC, gold-plated
Channels	Two
Coupling	DC
Maximum Input Voltage	±10 V DC (2 W) or 10 V RMS at 50
Bandwidth Limit Filter	35 MHz 2-pole Bessel filter (DC438)
Minimum Amplitude	1 V (peak to peak)
Impedance	50

Table 4.2: Configuration of Digitizer Card

4. **Four axis scanning setup:** The setup has four degree of freedom, three translations for positioning of transducer over plate and one rotational to arrange the transducers at a specific angle so as to get a desirable mode. The transducers are mounted in a holder and naturally coupled with water by putting plate & transducer setup in water. The excitation signal consisted of a negative spike pulse with pulse duration ranging from 10-70 ns. The least count for rotational motion is 0.1 degree. The maximum movement in X-direction is 120 cm, Y-direction is 70 cm, Z direction is 10 cm, and rotation allowed is 0-35 degree.

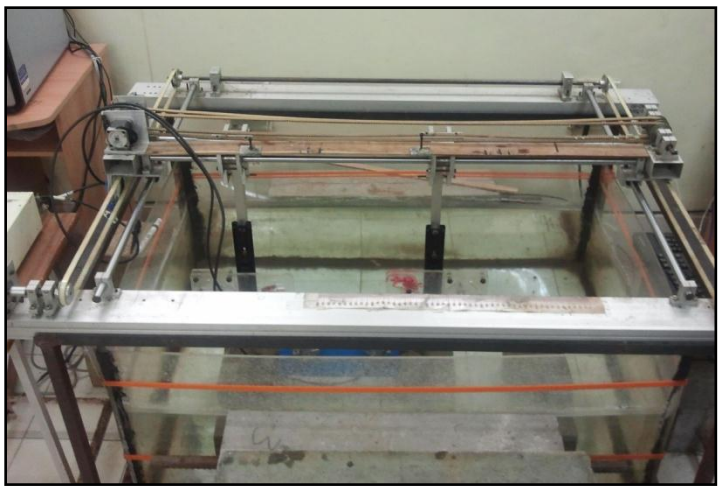


Figure 4.23: Four axis scanning setup

5. **Water tank:** The water tank used for this study is made up of Perspex of size 120cm x 72 cm x 50 cm. The speed of ultrasound in water is 1500 m/sec approx. The distance between the specimen and the bottom surface of the tank should be taken in such a way that the ultrasonic signal obtained from the specimen should not be affected by the reflected signal from the bottom surface.

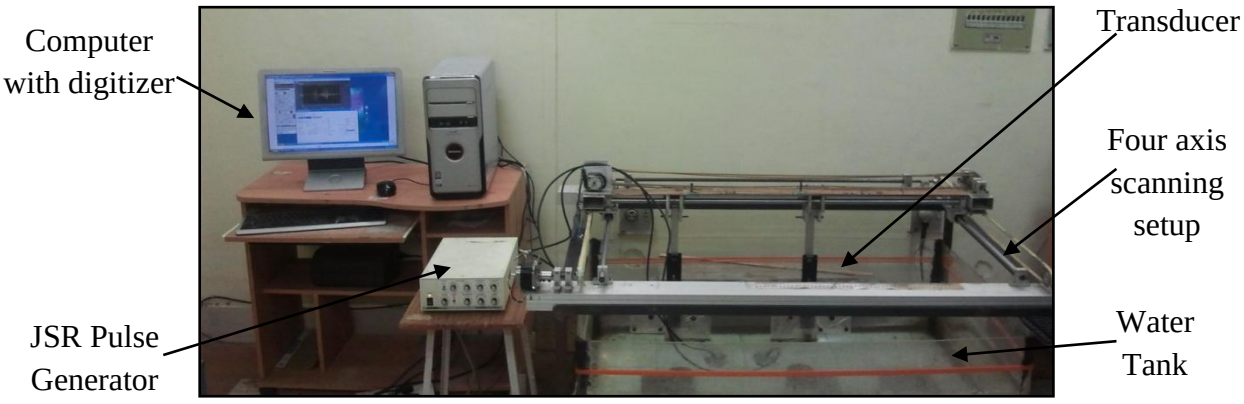


Figure 4.24: Ultrasonic experimental setup

4.5 Selection of the Frequency & Angle for damage detection

Transducer with central frequencies of 0.5 MHz has been used for the experiments. Higher frequencies have been avoided because at higher frequency, multiple wave modes exists & energy of the transducer is distributed among various modes. It is also difficult to excite a particular mode. Multiple modes & frequencies are not considered ideal for damage detection. Also higher frequency wave propagation has high attenuation. Different frequencies and modes

have different dispersion characteristics with a trend toward higher frequencies having slower energy transport velocities. Here the approach of finding the particular mode which is helpful for detecting the particular type of damage (delamination, notch and missing fibre) by testing the plate at various angles has been adopted. The angle of incidence which is particularly suitable to find particular damage more appreciably has been then selected. For different angles of incidence through transmission signal scanning has been done over laminate plate to check the health of specimen. First through transmission scanning has been taken over healthy region or healthy specimen & then comparison with that of defected region or specimen have been done. Loss in amplitude had helped in determining the severity of damage. Further pulse echo signatures have been recorded in the areas which are probably defect ridden. Pulse echo dete have been used to generate tomograms to represent the defective zone on the specimen.

4.6 Work plan

The work plan adopted for the study has been shown in the **Figure 4.25.**

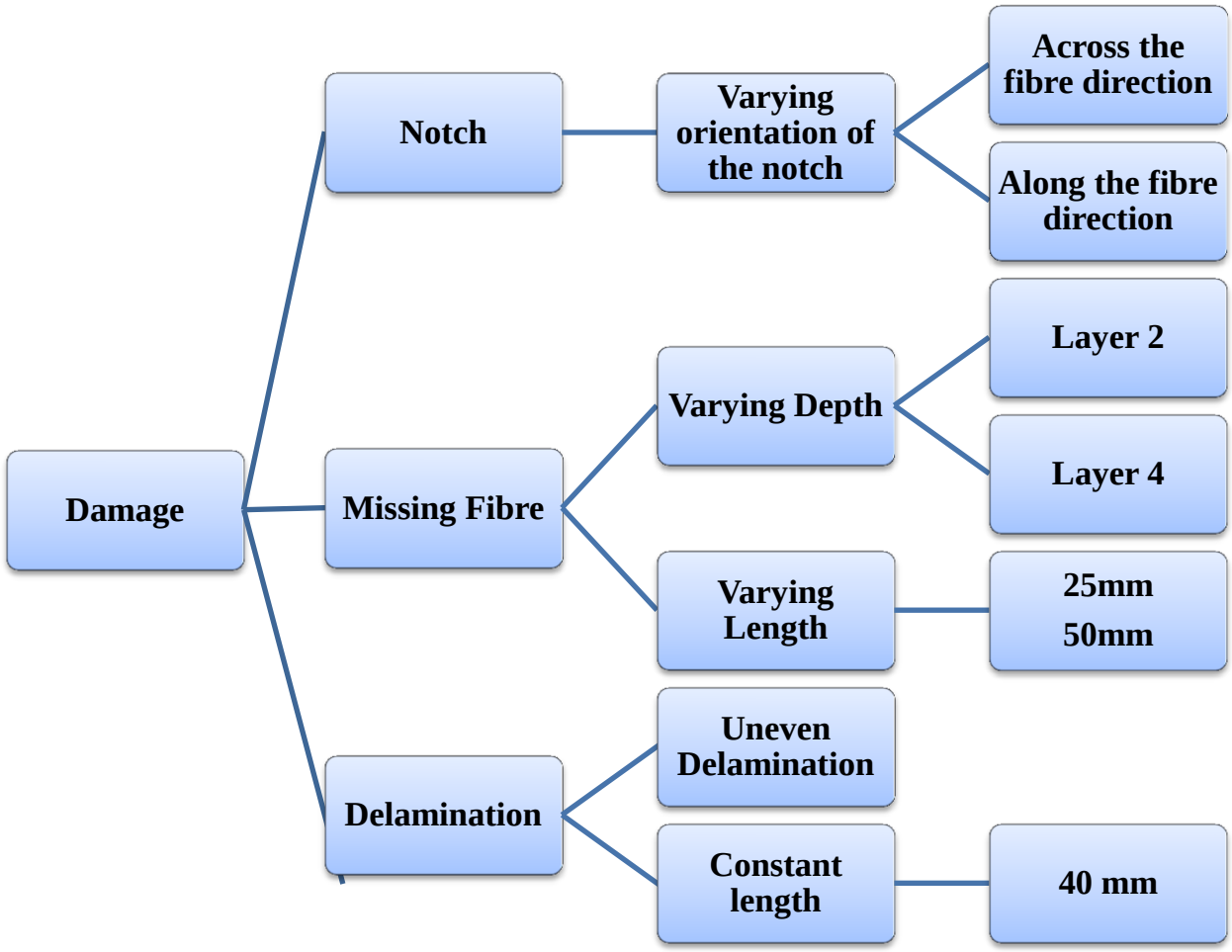


Figure 4.25: Work Plan

4.7 Closure

This chapter had discussed the method of fabrication of the GFRP laminate, methods of inducing the artificial defects, size/dimension of the specimens and the experimental setup required to carry out the study.

Also the work plan has been discussed in this chapter. In the following chapter results obtained after conducting respective experimental work on different specimens has been given & discussed.

Chapter 5:

RESULTS and DISCUSSION

5.1 Introduction

Damage detection has been an important area of concern in the design, operation, maintenance and repair of many military, industrial and civil structures and equipment involving plate structures, submerged in water. Experimentation has been conducted on the GFRP composite laminate according to the work plan discussed in the last chapter. This chapter discusses the results obtained after the experimental study and the discussions about the results obtained. Table of results has been formulated & comparison of different samples after seeded damage with that of healthy/reference specimens in terms of percentage decrease in ultrasonic signal have been discussed. Ultrasonic through transmission testing has been done on specimen to obtain reference/benchmark signature. Testing has been done for different angle setting & probe-probe distance to obtain the particular angle which generates the lamb mode most suitable to detect damage.

5.2 Notch Defect evaluation

The study of notch defect has been divided into two categories according to the notch orientation, in the first study notch has been cut in the direction perpendicular to the fibre and in the second study notch has been cut in same direction as that of fibre. The study has been done in four steps. Firstly the through transmission scanning has been done on healthy specimen on different locations. Then first three layers of the laminate has been cut and studied step by step respectively.

The extent of damage has been evaluated by comparing the peak to peak voltage amplitude signal obtained for different notch depths at the same location.

5.2.1 Notch defect across the fibre direction

In this study each fibre on the specimen has been cut, as the direction of the notch is perpendicular to the fibre. Through transmission scanning has been done on the four different locations (A, B, C and D) of the specimen shown in **Figure 5.1** along the width using transducer of frequency 0.5 MHz at different angles of incidence. The distance between the transducers was taken as 150 mm.

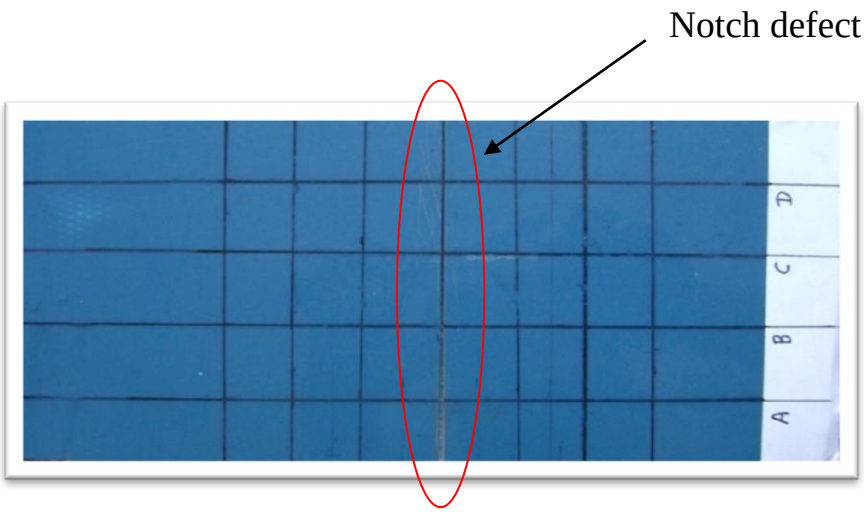


Figure 5.1: Specimen with the notch

- **Voltage signal**: **Table 5.1** shows the peak to peak voltage amplitude signal for different angles at each state (healthy, layer 1, layer 2 and layer 3) for the same settings and the probe to probe distance.

Angle of incidence (degree)	Healthy Specimen	Notch depth through epoxy (Layer 1)	Notch depth through Fibre (Layer 2)	Notch depth through epoxy (Layer 3)
14	1.31	1.18	0.96	0.89
16	1.64	1.48	1.21	1.10
18	2.03	1.86	1.40	1.39
20	2.44	2.16	1.74	1.64
22	2.76	2.19	1.96	1.81
24	3.00	2.61	2.05	1.93
26	2.92	2.45	1.93	1.90
28	2.73	2.53	1.97	1.90

Table 5.1: Voltage signal for notch defect at different angles

- **Percentage drop in signal: Table 5.2** shows the percentage drop in peak to peak voltage amplitude signal for the different depths of the notch that is after the removal of layer 1, layer 2 and layer 3 with reference to the healthy specimen at corresponding angles of incidence with respect to the healthy voltage signal.

Angle of incidence (degree)	Notch depth through epoxy (Layer 1)	Notch depth through Fibre (Layer 2)	Notch depth through epoxy (Layer 3)
14	10.23	26.79	32.56
16	10.17	26.50	33.33
18	8.30	30.87	31.29
20	11.44	28.62	32.72
22	20.70	28.88	34.32
24	12.75	31.73	35.60
26	16.07	33.81	34.88
28	7.33	27.86	30.28

Table 5.2: Percentage drop in peak to peak voltage amplitude for notch defect

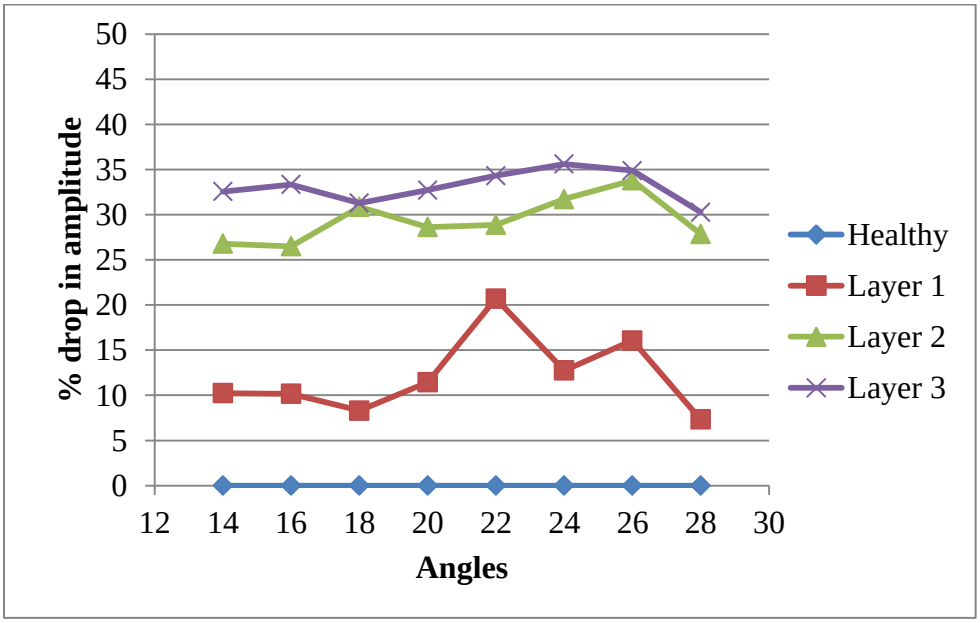


Figure 5.2: Percentage drop in voltage signal for notch defect at different angles

- **Ultrasonic investigations:** Scanning has been done for different angles of incidence but significant changes are observed when angles of incidence were in the range of 22° to 26°. The following graphs show the comparison of the ultrasonic signature between the

healthy specimen and the specimen with inflicted notch defect of varying depths cut through various layers of the specimen for three different angles.

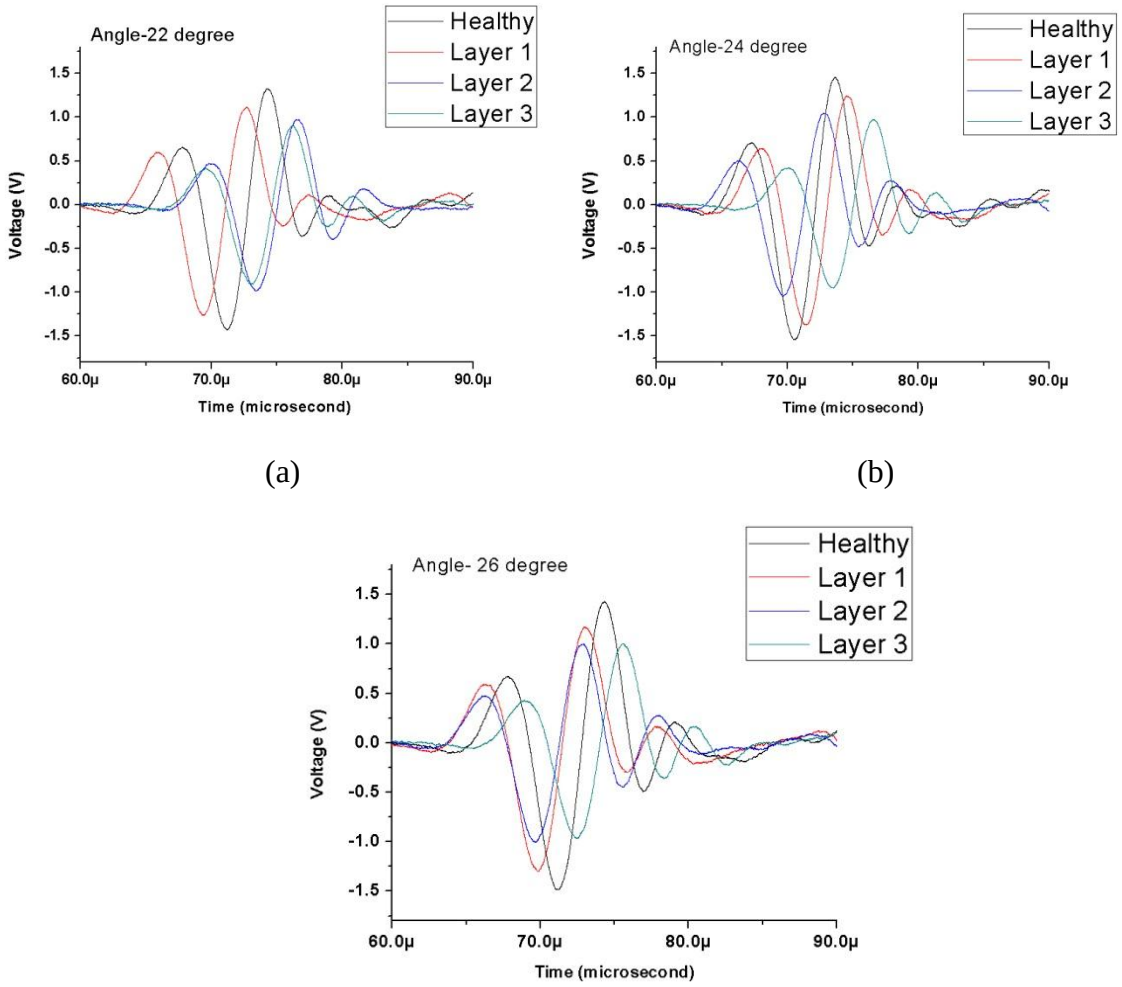


Figure 5.3: Through transmission signature for notch defect at angles (a) 22° (b) 24° (c) 26°

- **Tomogram:** Tomograms have been generated by the pulse echo signatures obtained at different locations of the specimen. The difference in the peak to peak voltage amplitude is represented by the colour difference in the tomogram. Tomograms for the notch defect have been generated for different angles of incidence but the most significant tomogram has been obtained at an angle 15°.

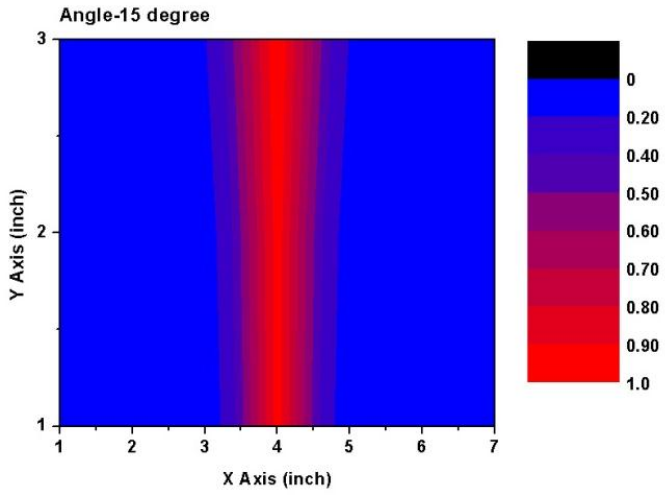


Figure 5.4: Tomogram for notch defect across the fibre

Discussion

It has been observed that the amplitude of the peak to peak voltage amplitude signal decreases with increase in the depth of the notch. **Table 5.1** shows that for each angle of incidence, the through transmission voltage signal is maximum for healthy specimen and minimum for the notch through layer 3. This variation in the voltage signal is due to the reduction in thickness of the specimen after the material removal. It can be concluded that the voltage signal decreases with increase in the depth of the notch.

Transducer of 0.5 MHz frequency at incident angle of 24° gives the maximum peak to peak voltage signal.

For the notch till the layer 1, the transducer at incident angle 22° gives the most significant percentage change in peak to peak amplitude. The drop in signal at 22° is about 20% of the healthy signal.

For the notch till layer 2 and layer 3, it has been observed that the variation in the percentage voltage drop of signal is almost similar when the angle of incidence is in the range of 22° to 26°. Out of these 24° offers maximum drop of 35.6%.

It has also been observed that after the removal of fibre layer (layer 2), there has been more percentage drop in peak to peak voltage amplitude than the removal of epoxy layer. It establishes that the majority of ultrasonic wave energy is carried by fibre as compared the epoxy.

5.2.2 Notch defect along fibre

In this study, the notch defect has been inflected in the direction of fibre. The through transmission scanning has been done at various angles with probe to probe distance as 80 mm. The three upper layers have been removed step wise from the laminate and the corresponding ultrasonic signatures have been recorded.

- **Voltage signal: Table 5.3** describes the amplitude of the peak to peak voltage signal for different angles at different depths of the notch using transducer of frequency 0.5 MHz.

Angle of incidence (degree)	Healthy Specimen	Notch depth through epoxy (Layer 1)	Notch depth through Fibre (Layer 2)	Notch depth through epoxy (Layer 3)
17	1.90	1.64	1.55	1.20
18	2.01	1.75	1.57	1.37
19	2.38	2.07	1.53	1.50
20	2.43	2.30	1.68	1.55
21	2.94	2.81	2.08	2.02
22	3.21	3.14	2.18	2.12
23	3.16	2.55	2.26	2.02
24	3.29	3.01	2.15	1.91
25	3.56	3.02	2.27	2.20

Table 5.3: Voltage signal for notch defect at different angles

Percentage drop in voltage: Table 5.4 shows the percentage drop in the amplitude of the peak to peak voltage signal for the different depths of the notch with reference to the healthy signature.

Angle of incidence (degree)	Notch depth through epoxy (Layer 1)	Notch depth through Fibre (Layer 2)	Notch depth through epoxy (Layer 3)
17	13.72	18.12	36.57
18	12.68	21.64	31.85
19	13.11	35.69	37.12

20	5.41	31.07	36.15
21	4.36	29.34	31.34
22	2.20	32.27	34.13
23	19.40	28.55	36.14
24	8.58	34.65	41.89
25	15.35	36.42	38.26

Table 5.4: Percentage drop in voltage signal for notch defect

- **Ultrasonic investigations:**

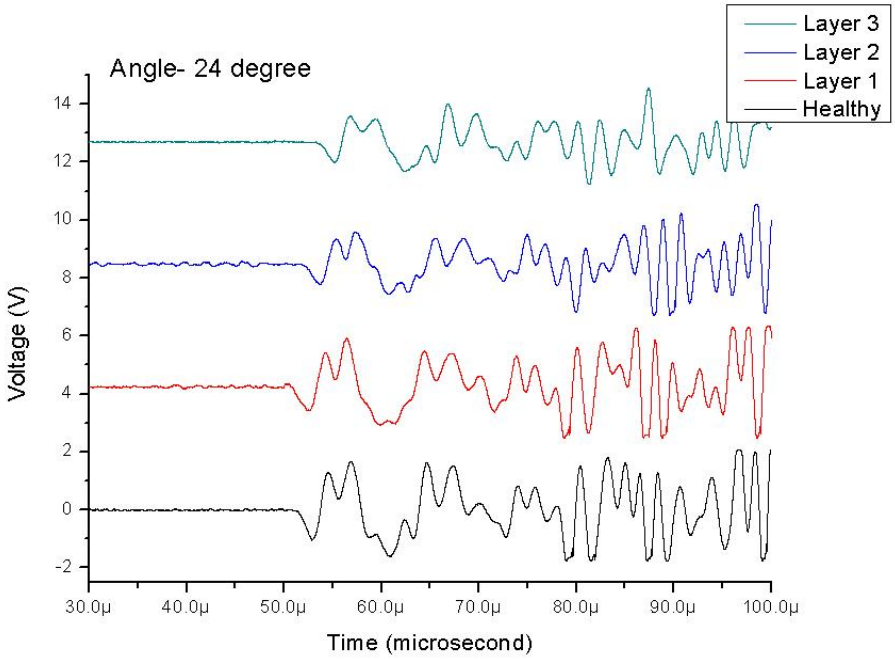


Figure 5.5: Through transmission signature for notch at angle 24°

Tomogram: Tomograms have been generated by the pulse echo signatures obtained at different locations of the specimen. The difference in the peak to peak voltage amplitude is represented by the colour difference in the tomogram. Tomograms for the notch defect along fibre direction have been generated for different angles of incidence but the most significant tomogram has been obtained at an angle 15°.

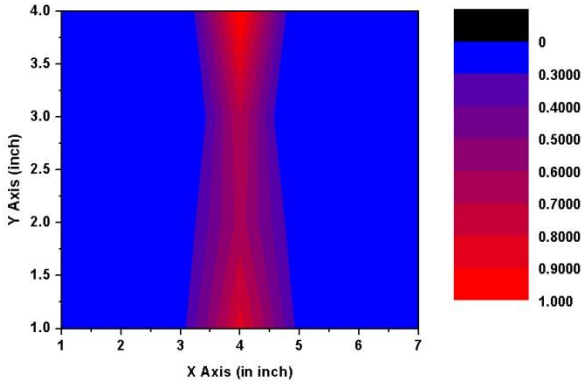


Figure 5.6: Tomogram for notch defect along the fibre direction

Discussion

It has been observed that the peak to peak voltage amplitude signal decreases with the extent of the notch. The percentage decrease in the voltage signal in this case has been approximately same as in the case of notch in the perpendicular direction of the fibre.

In comparison to the notch in the previous case the ultrasonic signature obtained in this study has been different. This may be attributed to the fact that in this case the scanning has been done across the fibres so the ultrasonic waves have to travel through different strands of fibre whereas in the previous case the ultrasonic waves travelled along the fibre of that layer thus avoiding multiple cross interactions with the fibre.

The detection of the notch defect with the transducer of frequency 0.5 MHz has been most significantly described at an angle of 24°. The percentage decrease in voltage signal after the notch had been applied till layer 3 has been 41% with reference to the healthy signal.

5.3 Evaluation for missing fibre

In this experiment, some portion of the fibre has been cut from the laminate during its fabrication as discussed in the previous chapter. The study has been divided into two categories. Firstly according to varying length of the missing fibre and secondly according to the varying depth in the laminate. The transducer of frequency 0.5 MHz has been used for this study. Through transmission scanning has been done on different angles to obtain the optimum angle which gives the most suitable observable changes for the defect. Pulse echo testing has been done at different angles to obtain the tomograms.

5.3.1 Evaluation of the missing fibre defect according to varying length

In this study, the defect has been induced in the upper fibre layer of the two ply laminate. The specimen has three different health conditions, viz healthy, missing fibre of length 25mm and missing fibre of length 50mm. The through transmission scanning has been done at different angles of incidence to obtain the variation in the ultrasonic voltage signal for healthy and the defected region and the relation between the variation of the ultrasonic signal with the change in the length of the missing fibre. The distance between the transducers has been taken as 150mm.

- **Voltage signal: Table 5.5** describes the peak to peak amplitude of the voltage signal at different angles for different regions of the specimen (healthy, missing fibre of length 50mm and missing fibre of length 25mm) at same working conditions.

Angles (degree)	Healthy specimen	Missing fibre (length 25mm)	Missing fibre (length 50mm)
14	1.31	0.75	0.60
16	1.64	0.87	0.69
18	2.02	0.96	0.77
20	2.44	1.09	0.86
22	2.76	1.13	0.96
24	2.99	1.15	0.99
26	2.91	1.13	0.97
28	2.72	1.19	0.97

Table 5.5: Voltage signal for missing fibre of varying length

- **Percentage drop in Voltage signal: Table 5.6** describes the variation in the percentage decrease in the peak to peak amplitude of the voltage signal for missing fibre region with reference to the healthy region signal of the specimen at different angles.

Angles (degree)	Missing fibre (length 25mm)	Missing fibre (length 50mm)
14	42.79	54.23
16	47.07	57.91
18	52.47	61.97

20	55.14	64.69
22	58.82	65.19
24	61.53	66.92
26	61.13	66.49
28	56.17	64.36

Table 5.6: Percentage drop in voltage signal for missing Fibre of varying length

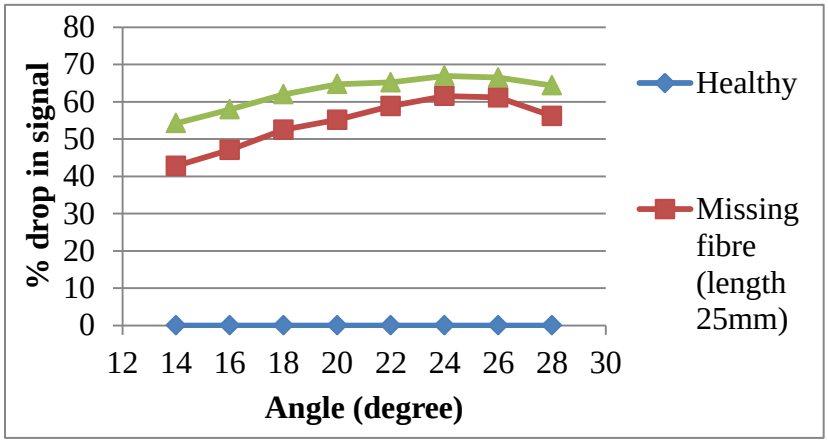
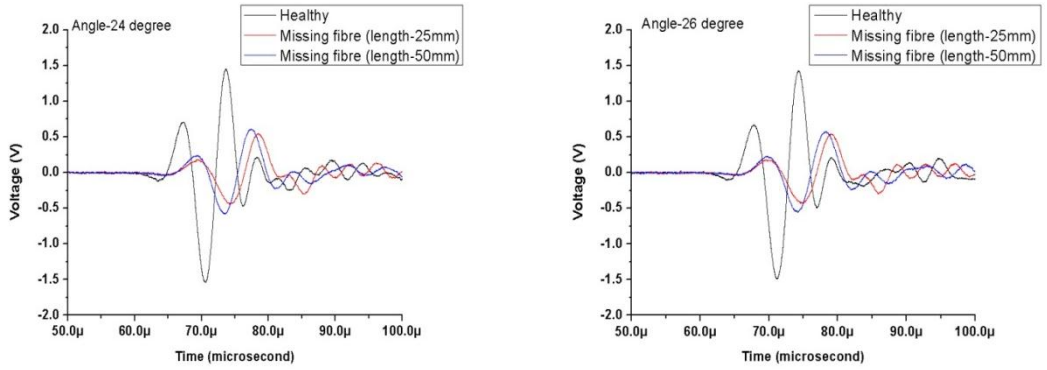


Figure 5.7: Percentage drop in voltage signal for missing Fibre of varying length

Ultrasonic investigations: The following graphs show the comparison of the ultrasonic signature between the healthy region and the region with the absence of fibre of varying length at angles 24° and 26°. Scanning has been done for eight different angles but these two angles shows the significant changes in the signal in comparison to the other angles.



(a) (b)

Figure 5.8: Through transmission ultrasonic signature for missing fibre of varying length at angles (a) 24° (b) 26°

- **Tomogram:-** Tomograms for missing fibre of varying extent (length) defect have been generated for different angles of incidence as shown in **Figure 5.9** but the most significant tomogram has been obtained at an angle 15°.

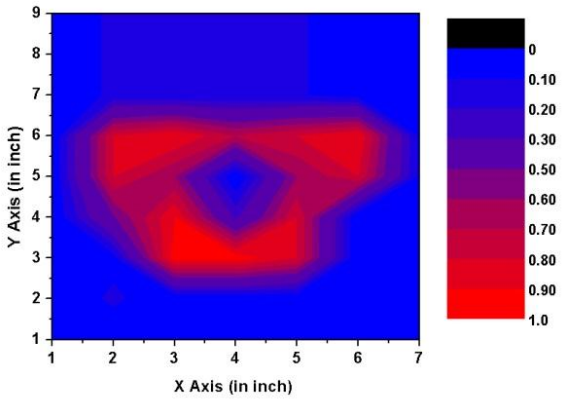


Figure 5.9: Tomogram for missing fibre defect of varying length at angle 15°

Discussion

It has been observed that the amplitude of the peak to peak voltage signal falls in the region of missing fibre.

From **Table 5.5**, it has been studied that by varying the extent of the missing fibre from 25mm to 50mm there has been 6-9% drop in the peak to peak amplitude of the voltage signal.

Testing has been done for different angles but 24° and 26° gives the most observable changes in the drop of ultrasonic signature. Out of these 24° is the most suitable angle for the detection of missing fibre defect in through transmission.

For the probe angle 24°, there has been about 62% drop in voltage signal in the missing fibre region of length 25 mm as compared to the healthy region. As the extent of missing fibre has been increased to 50 mm the drop in voltage signal increased to about 67%.

Finally it has been concluded that there has been large variation in the voltage signal in the missing fibre region as compared to the healthy region but there has been relatively less variation in the voltage signal by varying the extent (length) of the missing fibre.

5.3.2 Evaluation of the missing fibre defect according to the varying depth

In this study, the missing fibre defect has been evaluated according to the varying depth in the laminate. The study has been conducted for two depths in the two ply laminate which means in

the first study the missing fibre has been induced in the upper fibre layer (layer 2 of the laminate) and in the second study defect has been induced in the lower fibre layer (layer 4 of the laminate). The length of the missing fibre has been taken as 20 mm and it remains constant.

Lamb waves with frequency 0.5 MHz have been used for different angle settings to determine the defect at different depths of the laminated specimen. As different lamb wave modes are produced for different angle settings for particular frequency-thickness combinations. Different modes detect defects in different layers of the composites. So to detect defect in particular layer that particular mode need to be excited for defect evaluation.

5.3.2.1 Evaluation of the missing fibre defect in the upper fibre layer (layer 2 of the laminate)

- **Voltage Signal**: **Table 5.7** describes the peak to peak amplitude of the voltage signal at different angles for missing fibre region and the healthy region. Also the percentage drops in the voltage signal in the missing fibre region with reference to the healthy region.

Angles (degree)	Healthy region (V)	Missing fibre region (V)	% drop in peak to peak voltage amplitude
14	2.27	1.05	53.60
16	2.32	0.96	58.88
18	2.93	1.36	53.61
20	2.28	1.05	54.04
22	2.64	1.11	58.33
24	1.96	0.80	59.18
26	1.98	0.87	56.06
28	1.97	0.85	56.85

Table 5.7: Voltage signal for missing fibre defect in layer 2

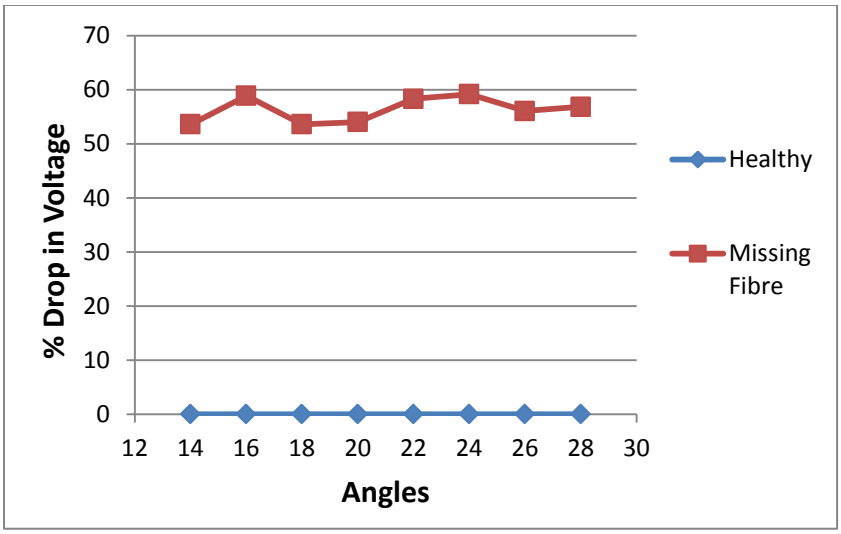


Figure 5.10: Percentage drop in voltage signal for missing fibre in layer 2

- **Ultrasonic investigations**: The following graphs show the comparison of the ultrasonic signature between the healthy region and the region with the absence of fibre at angles 22° and 24°. Scanning has been done for eight different angles but these two angles shows the significant changes in the signal in comparison to the other angles.

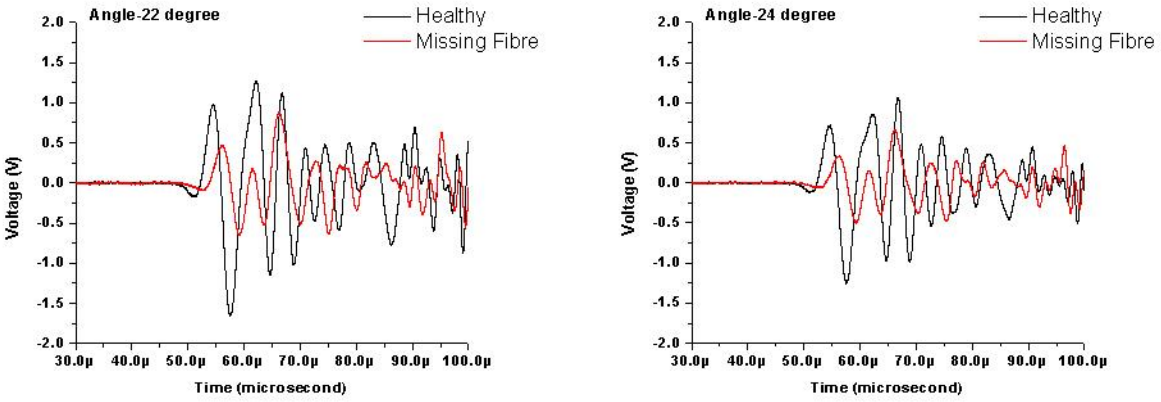


Figure 5.11: Through transmission signal for missing fibre defect in layer 2

Tomograms: Tomograms for the missing fibre defect have been generated for different angles of incidence as shown in **Figure 5.12** but the most significant tomogram has been obtained at an angle 15°.

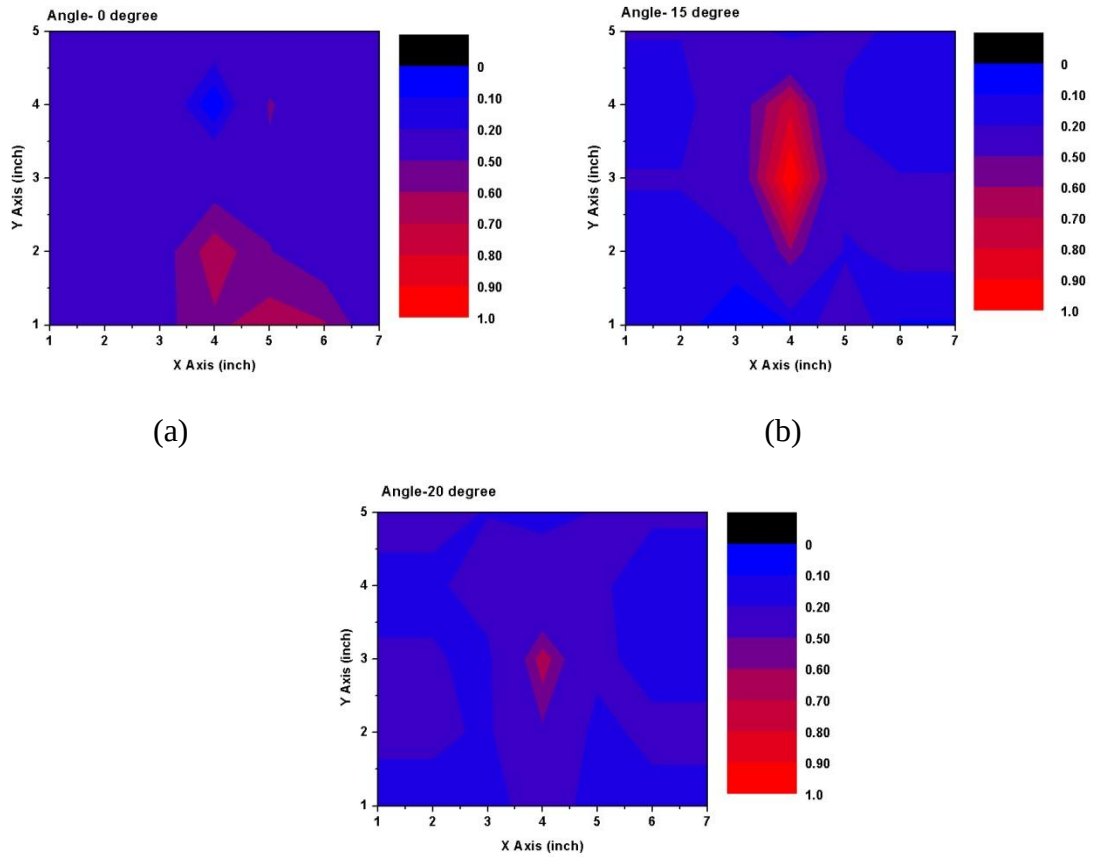


Figure 5.12: Tomograms for missing fibre in layer 2 at angles (a) 0° (b) 15° (c) 20°

5.3.2.2 Evaluation of the missing fibre defect in the lower fibre layer (layer 4 of the laminate)

- **Voltage signature: Table 5.8** describes the peak to peak amplitude of the voltage signal at different angles for missing fibre region and the healthy region. Also the percentage drops in the voltage signal in the missing fibre region with reference to the healthy region.

Angles (degree)	Healthy region (V)	Missing fibre region (V)	% drop in peak to peak voltage amplitude
12	0.79	0.45	42.95
14	1.50	0.76	49.23
16	1.80	0.69	61.42

18	2.32	0.68	70.89
20	1.98	0.50	74.69
22	1.98	0.49	76.03
24	3.59	0.90	74.88
26	2.77	0.60	78.17
28	3.12	0.71	77.50

Table 5.8: Voltage signal for missing fibre defect in layer 4

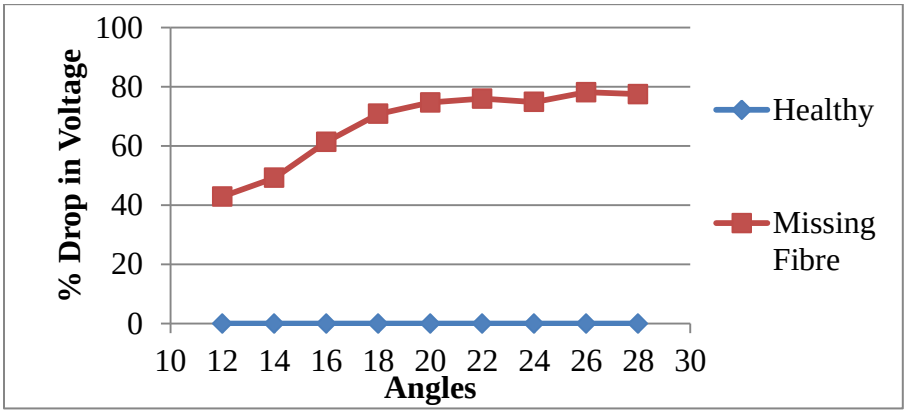


Figure 5.13: Percentage drop in voltage signal for missing fibre in layer 4

Ultrasonic investigations: The following graphs show the comparison of the ultrasonic signature between the healthy region and the region with the absence of fibre at angles 26° and 28°. Scanning has been done for nine different angles but these two angles shows the significant changes in the signal in comparison to the other angles.

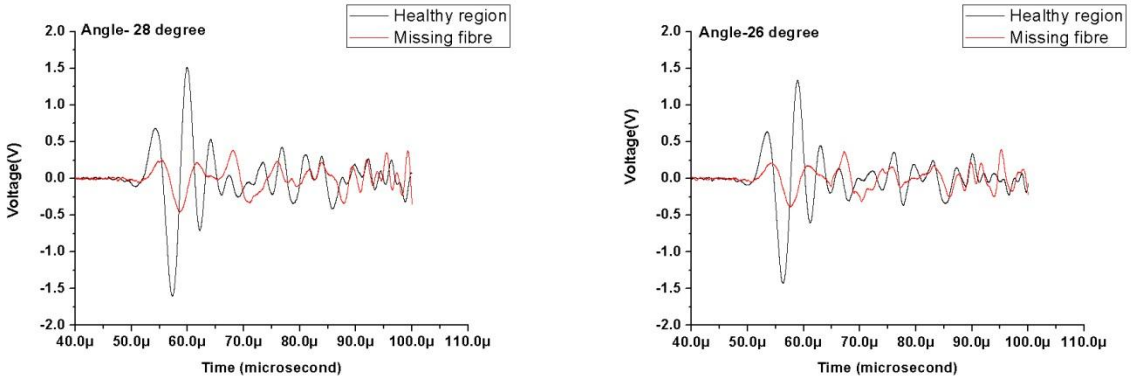


Figure 5.14: Through transmission signal for missing fibre defect in layer 4

Tomograms: Tomograms for the missing fibre defect have been generated for different angles of incidence as shown in **Figure 5.15**.

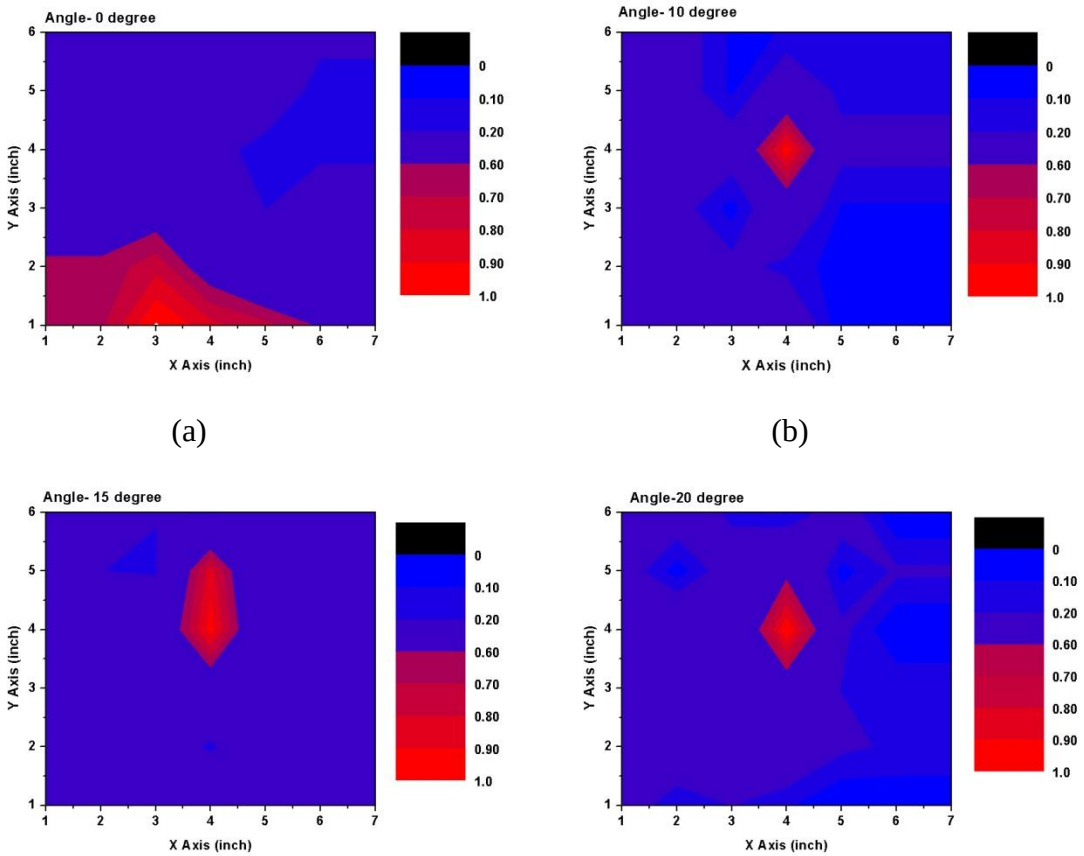


Figure 5.15: Tomograms for missing fibre in layer 4 at angles (a) 0° (b) 10° (c) 15° (d) 20°

Discussion

It has been observed that the amplitude of the voltage signal decreases in the region of missing fibre as compared to the healthy region for both the cases (layer 2 and layer 4).

The percentage decrease in the voltage signal for the defect in layer 4 has been comparatively more than the defect in the layer 2.

In case of missing fibre in layer 2, the probe angle 24° gives the most suitable results. The amplitude of the peak to peak voltage signal in the missing fibre region decreases to 59% of the voltage signal in the healthy region. Whereas in case of missing fibre in layer 4, the probe angle 26° has been most suitable to detect the missing fibre defect. The voltage signal in the defected region decreases to about 78% of the voltage signal in the healthy region.

Tomograms have been obtained for different angles. It has been observed that, angle 15° gives the most suitable tomogram which clearly localize the defected region. Some variations in the colour have been shown in the healthy region on the graph. As the specimen is non-homogeneous and also fabricated with the hand layup operations, this might be the reason for this variation.

5.4 Evaluation for delamination

Delamination is one of the major causes of failure in composite laminated structures. Delamination is de-bonding in between the adjacent layers due to the application of load or environmental degradation. So in order to identify & evaluate the delamination, experimental study about delamination has been done. The study has been divided into two categories. In the first study the delamination of length 40 mm has been induced in the specimen. For second study uneven delamination has been done. Delamination has been introduced between the two glass fibre layers (layer 3 of the laminate). The through transmission scanning has been done on different angles to obtain the variation in the ultrasonic voltage signal between the healthy and the delaminated region. Also the pulse echo scanning has been done to localize the defect by generating the tomograms.

5.4.1 Delamination of constant length (40 mm)

- **Voltage signal:** The voltage signal of the healthy and the delaminated region has been shown in the **Table 5.9** given below. Also the percentage drop in the peak to peak amplitude in the delaminated region with reference to the healthy region has been shown.

Angles (degree)	Healthy (V)	Delamination (V)	% drop in peak to peak voltage amplitude
16	2.55	0.99	61.24
18	3.11	1.10	64.44
20	3.48	1.19	65.79
22	3.75	1.25	66.53
24	3.81	1.28	66.32
26	3.54	1.11	68.51
28	3.35	1.07	67.99

Table 5.9: Voltage signal for delamination of 40 mm length

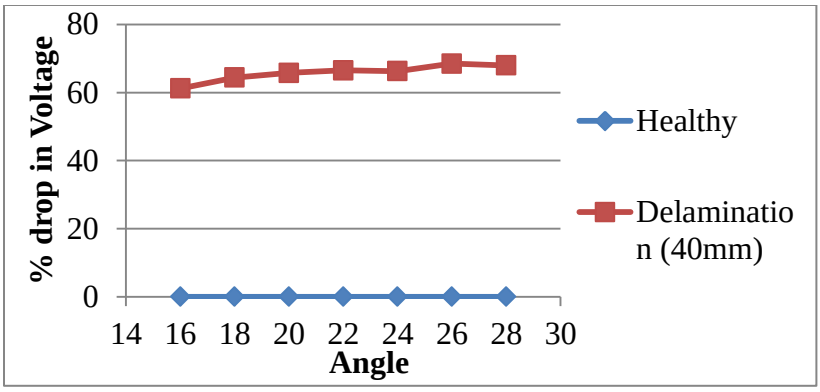


Figure 5.16: Percentage drop in voltage signal for delamination (length 40 mm)

Ultrasonic investigations: The following graphs show the comparison of the ultrasonic signature between the healthy region and the region with the presence of delamination at angles 22°, 24°, 26° and 28°.

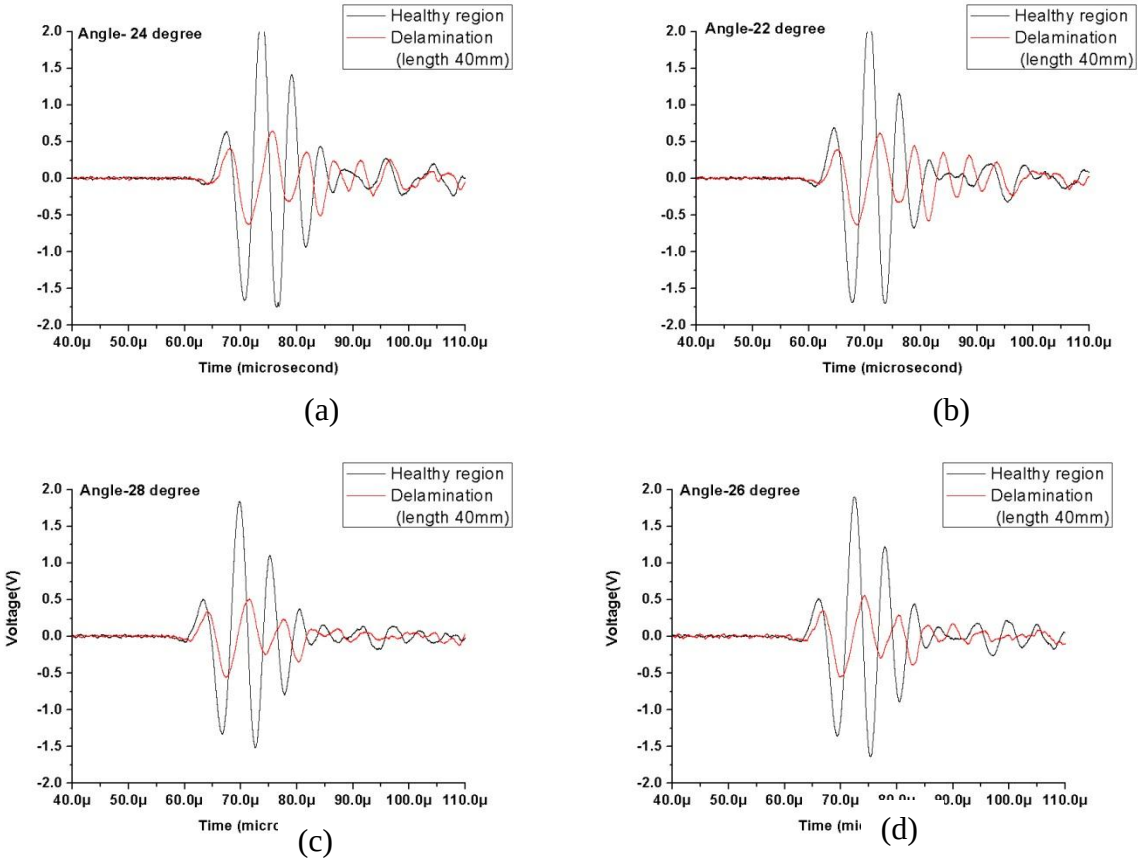


Figure 5.17: Through transmission signal for delamination (length 40 mm) at angles (a) 22° (b) 24° (c) 26° (d) 28°

Tomogram: Tomograms for the missing fibre defect have been generated for different angles of incidence as shown in **Figure 5.18.**

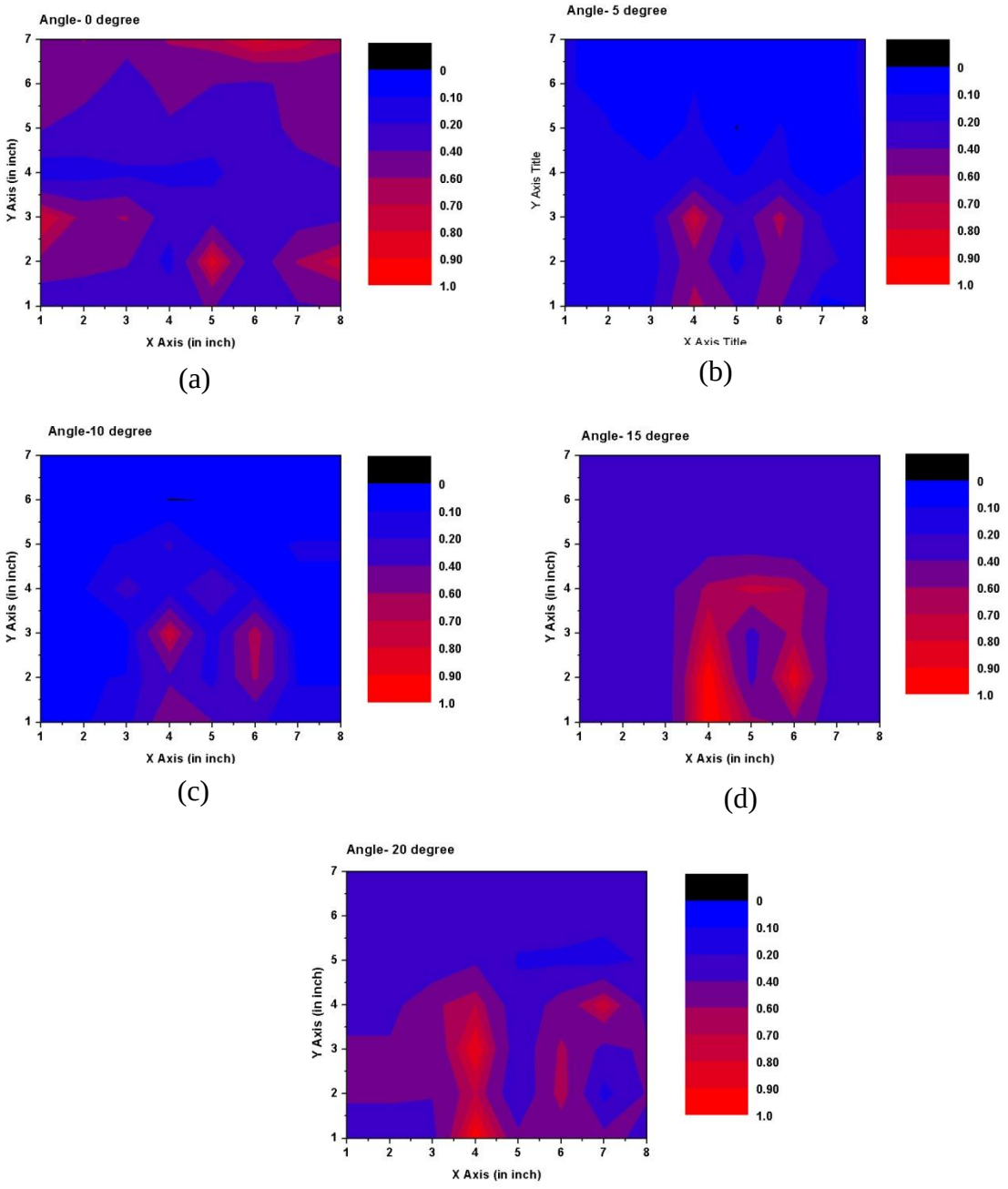


Figure 5.18: Tomograms for delamination (length 40 mm) in layer 4 at angles (a) 0° (b) 5° (c) 10° (d) 15°

Discussion

It has been observed that the amplitude of the peak to peak voltage signal decreases in the delaminated region as compared to the healthy region.

Through transmission scanning has been done for different angles, out of these 26° gives the most suitable results. The voltage signal in the delaminated region decreases to about 68% of the signal in the healthy region.

From **Table 5.9** it has been observed that the variation in the voltage signal in the delaminated region from healthy region between different angles has been very less.

5.4.2 Evaluation for uneven delamination

This study has been conducted to detect the delamination for those cases in which the delaminated region does not have any regular pattern. As in the real time applications the delamination occurs in an uneven pattern therefore it needs to be studied.

- **Voltage signal: Table 5.10** describes the voltage signal for uneven delamination for different angles at different locations on the specimen. The location A comes under the healthy region. Whereas from location B to E the delamination has been induced in an uneven pattern. The pulser/ receiver settings have been kept same for all locations on the specimen for that angle.

Angles / **Location**	**14°**	**16°**	**18°**	**20°**	**22°**	**24°**	**26°**	**28°**	**30°**
A (Healthy)	1.95	2.80	2.66	2.45	2.27	2.09	2.75	2.20	2.67
B	2.36	2.72	2.02	1.61	0.76	0.63	1.38	1.70	1.60
C	1.06	1.67	1.44	1.50	1.00	0.92	1.23	1.09	1.20
D	0.86	1.46	1.01	0.79	0.46	0.33	0.55	0.65	0.91
E	3.35	3.64	2.65	1.70	0.60	0.37	0.82	0.68	0.84

Table 5.10:Voltage signal for the uneven delamination

- **Percentage drop in voltage signal:**

Angles / Location	14°	16°	18°	20°	22°	24°	26°	28°	30°
A (Healthy)	0	0	0	0	0	0	0	0	0
B	-21.07	2.66	24.12	34.43	66.72	69.91	49.82	22.68	40.05
C	45.58	40.51	45.85	38.91	55.99	55.98	55.32	50.31	54.97
D	55.92	47.80	61.99	67.76	79.60	84.02	80.05	70.59	65.90
E	-72.06	-29.87	0.42	30.79	73.59	82.39	70.12	68.98	68.51

Table 5.11: Percentage drop in the voltage signal for uneven delamination

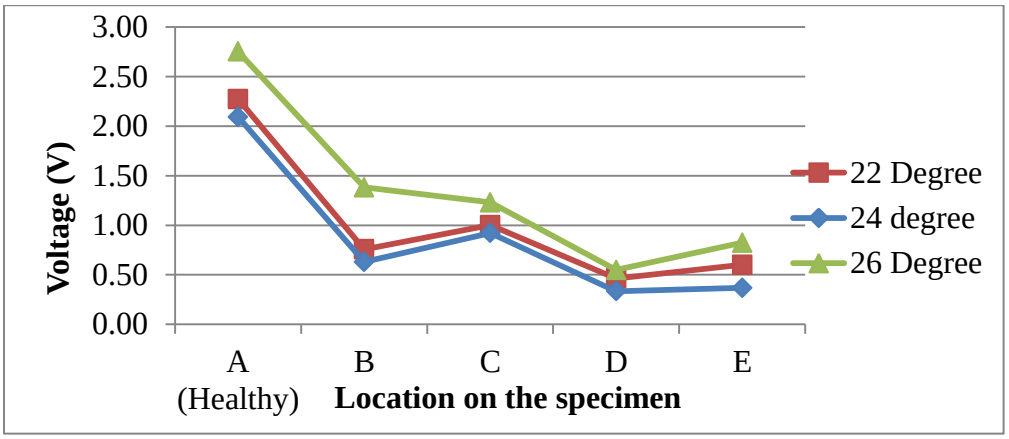


Figure 5.19: Voltage signal for uneven delamination at different locations

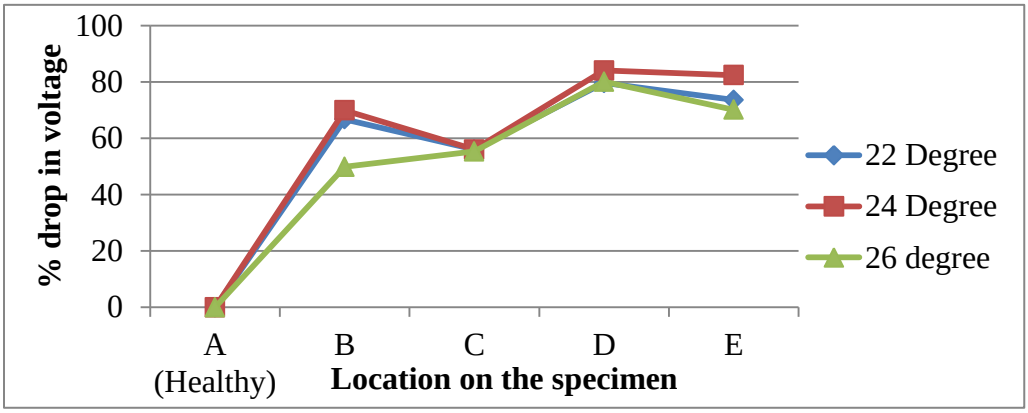


Figure 5.20: Percentage drop in voltage signal for uneven delamination at different locations

Ultrasonic investigations: The following graphs shows the comparison between the ultrasonic voltage signal in the delaminated region at location 'D' and the healthy region at location 'A' for four angles.

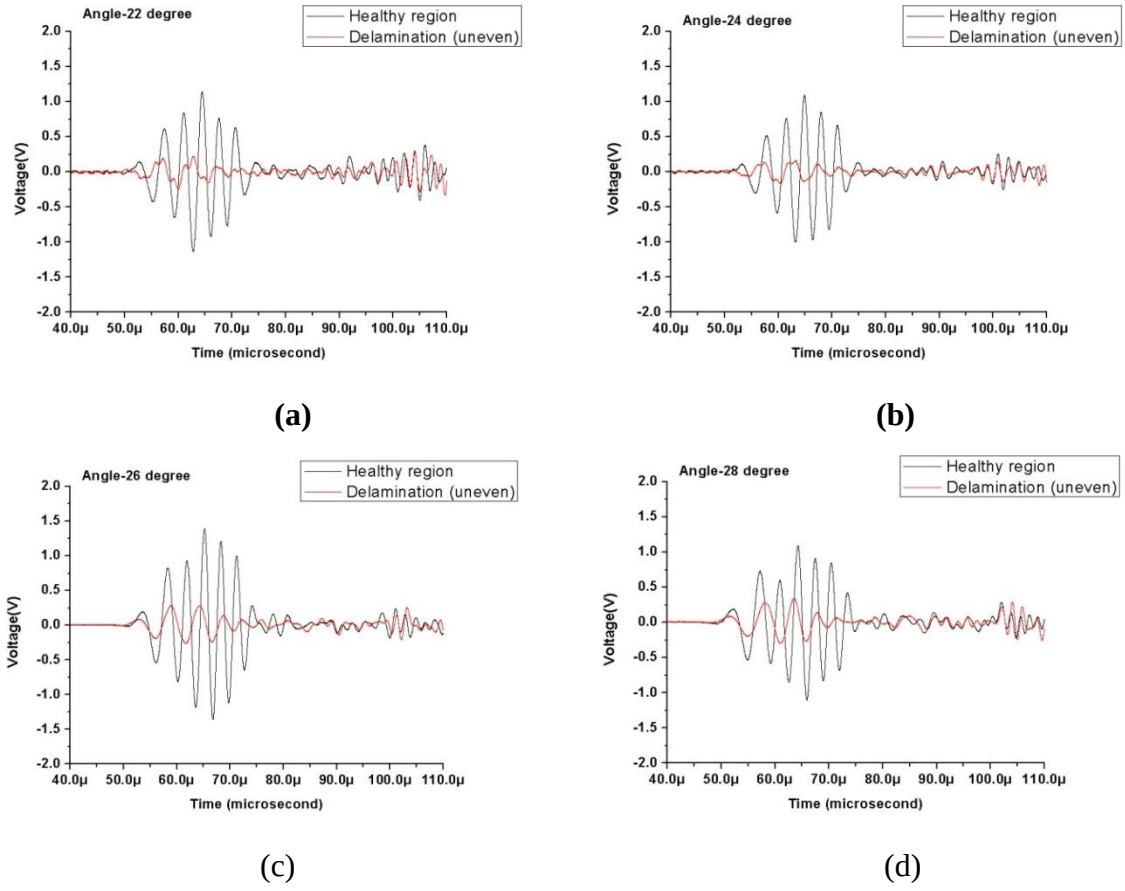


Figure 5.21: Through transmission signal for uneven delamination

- **Tomogram:-** Tomograms for uneven delamination defect have been generated for different angles of incidence as shown in **Figure 5.22** but the most significant tomogram has been obtained at an angle 15°.

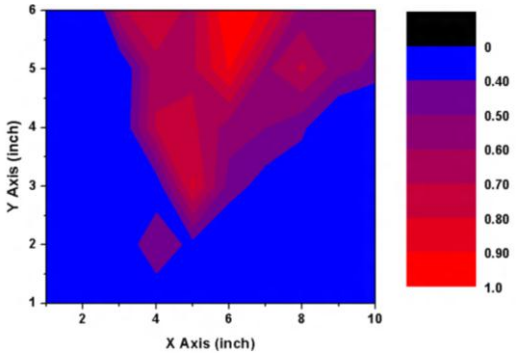


Figure 5.22: Tomogram for uneven delamation at angle 15°

Discussion

From the above experimental study, it has been observed that the amplitude of the peak to peak voltage signal in the delaminated region decreases as compared to the voltage signal in the healthy region.

In actual, the specimen has been delaminated in such a way that location A comes under the healthy region whereas from location B to E, extend of delamination varies in an irregular pattern. The drop in ultrasonic voltage signal increases with the increase in the extent of delamination. It has been concluded that the variation in the drop of signal is the function of the extent of delamination.

For each location the maximum percentage drop in the voltage signal has been detected at angle 24°. Therefore the optimum angle for detecting the uneven delamination defect is 24°.

Chapter 6:
CONCLUSIONS

The experimental study carried out on GFRP laminates with seeded external and internal defects shows that ultrasonic guided waves can be effectively used for detecting the commonly prevalent damages in laminates. Different modes at different frequencies are sensitive to different types of defects. Following conclusions can be drawn from this study.

6.1 Evaluation for notch defect

Glass fibre laminate with seeded notch defect of varying depths and with different orientation with respect to fibre direction shows considerable changes in through transmission peak to peak voltage amplitude. Notch defect for both the orientations has been most significantly detected at an angle of 24°. The percentage decrease in voltage signal after the notch had been applied through layer 3 has been 35% for notch across the fibre direction and 41% for the notch along the fibre direction with reference to the healthy signal. It can be concluded that with increase in depth of the notch there has been a consistent fall in the through transmission signal. Presence of notch defect also affects the pulse echo signature subsequently. Data obtained from the pulse echo signatures can be used to pictorially represent the defect in the form of tomogram.

6.2 Evaluation for missing fibre defect

The study for missing fibre defect has shown that ultrasonic testing is able to evaluate internal defect in the laminated specimen. From the experiment conducted it has been depicted that there was drop in through transmission signal by 61% over the region with missing fibre of length 25mm as compared to the healthy region. Further this drop increases to 67% with increase in missing fibre length to 50mm. Also Guided waves had determined the missing fibre defect in between different layers of laminated specimen at different depth/layers. At different angles different modes have been generated which detected defects in between different layers. The missing fibre defect in layer two of the laminate has been most significantly detected at an angle of 24°. Whereas 26° describes the missing fibre defect in layer four of the laminate most significantly. The internal defect in the form of missing fibre has been localized by pulse echo signatures by generating the tomograms at an angle of incidence 15°.

6.3 Evaluation of delamination

Glass fibre laminate subjected to delamination defect has been detected in through transmission. The peak to peak voltage amplitude signal shows considerable changes in the delaminated region with reference to the healthy region. The signal falls to about 68% for the delamination of length 40mm from the voltage signal in healthy region. The delamination defect has been more described for the higher angle of the range 22° to 28°. Tomograms have been generated to determine the location of the defect.

So it has been concluded that ultrasonic guided waves can be used as NDT tool to examine the structure health of GFRP laminate for different types of internal and external defects by examining the loss in guided wave signal amplitude.

6.4 Scope of future work

1. Laminates can be fabricated by spray lay-up operation or autoclave moulding.
2. Bidirectional glass fibre can be used for the fabrication of the laminates.
3. Sensitivity and the selection of the ideal modes for particular type of damage can be analytically evaluated and tested.
4. The number of layers of the laminate can be increased with different types of damages in varying depths.
5. Damage caused to composite laminates by different loading conditions like fatigue loading, impact loading can be studied using guided waves.
6. Numerical modelling of NDE of composite laminates with seeded defects can be undertaken and may be used to validate the experimental results.

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