DAMAGE DETECTION & EVALUATION IN GLASS FIBRE REINFORCED POLYMER LAMINATED COMPOSITES

A
Thesis Report

Submitted in partial fulfillment of the requirement for the award of degree of

MASTER OF ENGINEERING
In
CAD/CAM & ROBOTICS

Submitted By

Gurdyal Singh
(Roll No. 800981009)

Under Guidance of

Mr. Sandeep Sharma
Assistant Professor
Deptt.of Mechanical Engg.
Thapar University, Patiala

Dr. Rahul Chhibber
Assistant Professor
Deptt.of Mechanical Engg.
Thapar University, Patiala

DEPARTMENT OF MECHANICAL ENGINEERING
THAPAR UNIVERSITY
PATIALA-147004, INDIA

CERTIFICATE

This is to certify that the work in this thesis report entitled "**Damage Detection & Evaluation in Glass Fibre Reinforced Polymer Laminated Composites"** submitted in partial fulfillment of requirement for the award of **Master of Engineering Degree in CAD/CAM & Robotics** in the 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 and Dr. Rahul Chhibber, 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.

Dated: **Gurdyal Singh**

This is to certify that the above declaration made by the student concern is correct to the best of my knowledge and belief.

Rahul Chhibber 14/7/2011

Mr. Sandeep Sharma
Assistant Professor
Deptt.of Mechanical Engg.
Thapar University, Patiala

Dr. Rahul Chhibber
Assistant Professor
Deptt.of Mechanical Engg
Thapar University, Patiala

Dr. Ajay Batish
Professor & Head
Deptt. of Mechanical Engg.
Thapar University, Patiala

Dr. S. K. Mohapatra
Dean of Academic Affairs
Thapar University, Patiala

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Gurdyal Singh

Roll No: 800981009

ABSTRACT

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 due to environmental degradation or harsh loading conditions (delamination, cracks).

Cost effective & reliable damage evaluation is quite 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 of health of subject. 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 techniques include pulse echo and pulse transmission technique, where stress waves are introduced into subject structure and reflections (echoes) are returned to a receiver from internal imperfections. Pulse echo is used to locate the exact position of damage and pulse transmission is used to know 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.

This thesis presents results of evaluation of damages caused in GFRP laminated specimens subjected to hygro-thermal & mechanical loading. Also simulated delamination type defects of varying extent & location have been studied with help of ultrasonic guided waves in terms of their effects on corresponding signal. For hygro-thermal loading, two layers unidirectional glass fibre reinforced laminate specimens have been subjected to water & NaOH solution (5% by weight) at 45°C temperature for 15 & 30 days. Changes in strength of specimens has been evaluated & compared to ultrasonic signal. Similarly the specimens have been subjected to different levels of loading (25%, 50% & 75% of the ultimate tensile load) to inflict the damages due to loading in working conditions. Subsequently changes in ultrasonic test signatures for these specimens have been recorded & correlated to the ultrasonic signatures of unloaded specimens. Also simulated delamination defects of varying extent & location in different layers have been studied using ultrasonic testing.

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CHAPTER 1 INTRODUCTION

1.1 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, and 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.

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 of health of subject. 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 has been divided into two main parts:-

Part A: - Gives introduction about composites, types of fibre reinforced polymers, laminate composites, methods of manufacturing the composites & commonly occurring damage to composite structures.

Part B: - Presents the ultrasonic technique as NDT tool to detect & evaluate the damage.

PART A

1.2 Composite materials [1]

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, fiberglass, mud, bricks, and natural composites such as wood, rock etc.

1.2.1 Constituents of composite [2]

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

- **a)** Resin or matrix
- **b)** Reinforcement

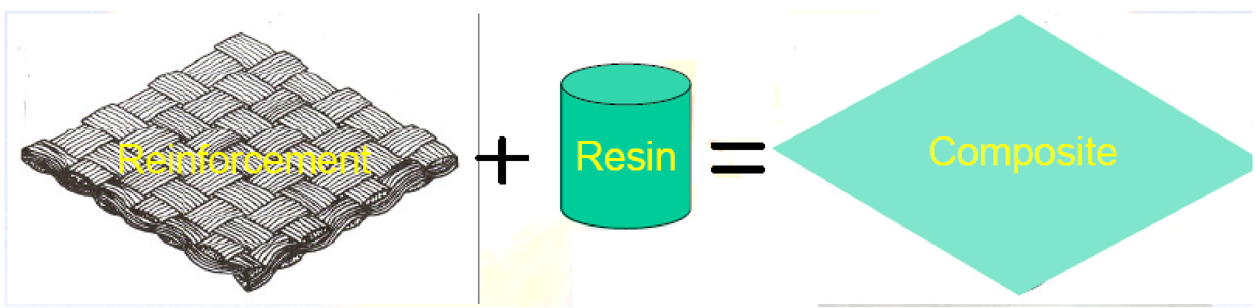


Fig 1.1 Composite [3]

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.

1.2.2 Classification systems of composites [4]

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.

1.2.2.1 Classification I

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

Metal Matrix Composites are composed of a metallic matrix (aluminum, 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).

1.2.2.2 Classification II

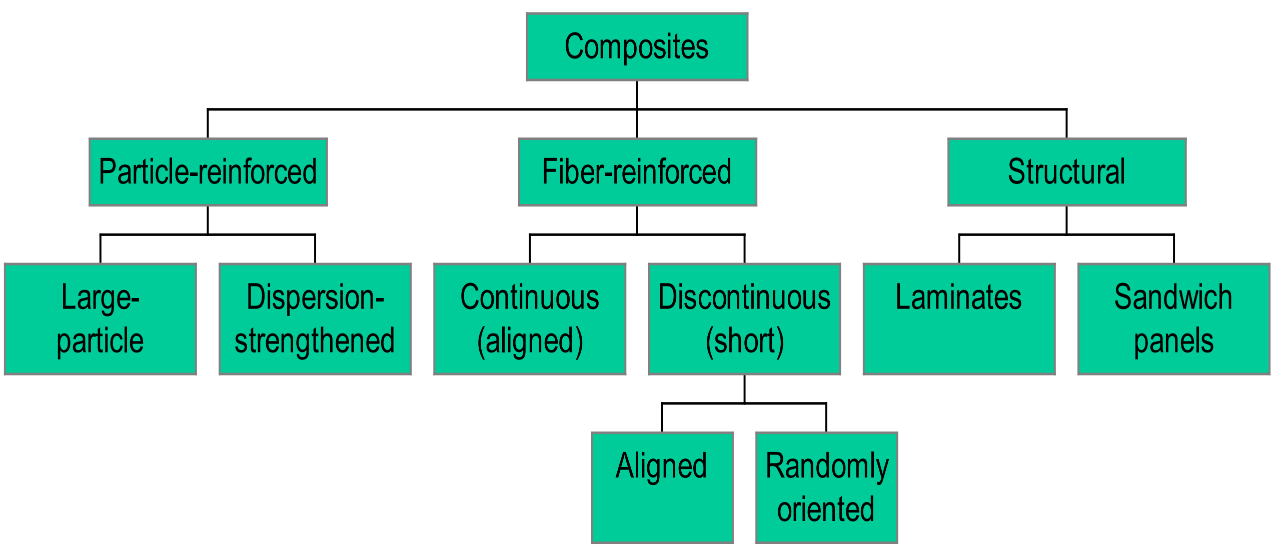


Fig 1.2 Classification of composite

1) Particle-reinforced Composites

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

1. Composites with random orientation of *particles*.

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

2) Fibre-reinforced Composites

1. 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).
   a) Composites with random orientation of fibres.
   b) Composites with preferred orientation of fibres.
2. Long-fibre reinforced composites: -Long-fibre reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibres.
   a) Unidirectional orientation of fibres.
   b) Bidirectional orientation of fibres (woven).

3) Laminate Composites

The most common form in which fiber-reinforced composites are used in structural applications is called a laminate, which is made by stacking a number of thin layers of fibers 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.

1.2.3 Properties of composites

Composites have superior properties as compared to conventional metals & alloys. They possess excellent strength & stiffness, light in weight; possess high resistance to corrosion, chemicals and other weathering agents. They can be molded to any shape and size with required mechanical properties in different directions. Composites have high strength to weight ratio.

1.2.4 Advantages of composites

Composite structures have the advantages like good dimensional stability (Space based telescope), low dielectric, corrosion resistance & weight saving.

But some disadvantages associated with composites are high production cost, difficult to repair; design analysis must consider many variables, low inter-laminar strength & poor conductivity.

1.2.5 Applications of composite materials [6]

Major application areas include aircraft, space, automotive, sporting goods, marine and infrastructure. Composites are also used in electronics (e.g., printed circuit boards), building construction (e.g. floor beams), furniture (e.g. chair springs), power industry (e.g., transformer housing), oil industry (e.g., offshore oil platforms and oil sucker rods used in lifting underground oil), medical industry (e.g., bone plates for fracture fixation, implants, and prosthetics), and in many industrial products such as step ladders, oxygen tanks, and power transmission shafts. Potential use of fiber-reinforced composites exists in many engineering fields. Putting them to actual use requires careful design practice and appropriate process development based on the understanding of their unique mechanical, physical and thermal characteristics.

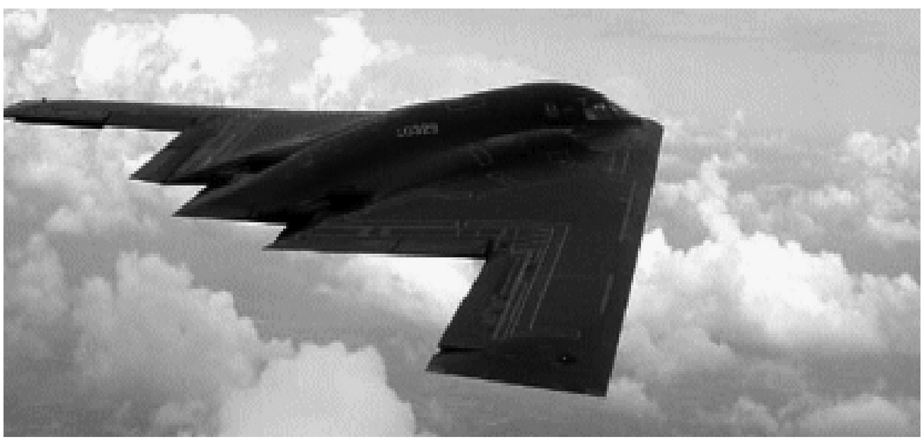


Fig 1.3 Stealth aircraft [6]

1.2.6 Types of fibre used in composites [6]

1.2.6.1 Glass Fibre

Glass fibres are made of silicon oxide with addition of small amounts of other oxides.

Main types of glass fibres:

- E-glass
- S-glass.

E-glass is the mostly used, and takes its name from its good electrical properties. S-glass type is very strong (S-glass), stiff, and temperature resistant.

(a) (b)

Fig 1.4 (a) Woven fabric of glass fibre (b) Roll of glass fibre

By blending quarry products (sand, kaolin, limestone etc.) at 1,600°C, liquid glass is formed. The liquid is passed through micro-fine bushings and simultaneously cooled to produce glass fibre filaments from 5-24μm in diameter. The filaments are drawn together into a strand (closely associated) or roving (loosely associated), and coated with a “size” to provide filament cohesion and protect the glass from abrasion. By variation of the recipe, different types of glass can be produced.

Glass fibre is available in the following forms:

1) Continuous Fibre

2) Chopped strands

3) Woven Fabric.

1.2.6.2 Aramid (Kevlar) fibre

Aramid fibre is a man-made organic polymer (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend. The bright golden yellow filaments produced can have a range of properties, but all have high strength and low density giving very high specific strength. All grades have good resistance to impact, and lower modulus grades are used extensively in ballistic applications. Compressive strength, however, is only similar to that of E glass.

1.2.6.3 Carbon fibre

Carbon fibres are created when polyacrylonitrile fibres (PAN), Pitch resins, or Rayon are carbonized (through oxidation and thermal pyrolysis) at high temperatures. Carbon fibers are manufactured in diameters analogous to glass fibers with diameters ranging from 9 to 17 µm. These fibers wound into larger threads for transportation and further production processes.

Further production processes include weaving or braiding into carbon fabrics, cloths and mats analogous to those described for glass that can then be used in actual reinforcement processes

(a) (b)

Fig 1.5 (a) Woven fabric of carbon fibre (b) Roll of carbon fibre

1.2.7 Types of fibre reinforced polymers

- Carbon Fibre Reinforced Polymer (CFRP)
- Glass Fibre Reinforced Polymer (GFRP)
- Boron Fibre Reinforced Polymer (BFRP)
- Aramid Fibre Reinforced Polymer (AFRP)

Table 1.1 Mechanical properties of specified fibre types [6]

Type of Fibre	Property			
	Tensile Strength	Relative Density	Young's Modulus	Failure Strain
	GPa	Kg/m^3	GPa	%
Carbon HS	3.5	1.8	220-240	1.5-2.2
Carbon HM	3.5	1.8	290-300	1.3-2.0
Carbon UHM	3.4-5.5	2	350-450	0.7-1.0
Aramid	2.0-3.0	1.4	60	4.4
Kevlar	3	1.5	130	2.3
E-glass	2.4	2.6	73	3
S-glass	3.4	2.5	86	3.9

HS: High Strength
HM: High Modulus
UHM: Ultra High Modulus

For the present research work, E-glass fibre reinforced polymer sheet has been used.

1.2.8 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.

1.2.8.1 Advantages of GFRP

The principal advantages of glass fibers 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 fibers), sensitivity to abrasion during handling (which frequently decreases its tensile strength), relatively low fatigue resistance, and high hardness (which causes excessive wear on molding dies and cutting tools).

1.2.8.2 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

1.2.9 Laminated composites

The most common form in which fiber-reinforced composites are used in structural applications is called a laminate, which is made by stacking a number of thin layers of fibers 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.

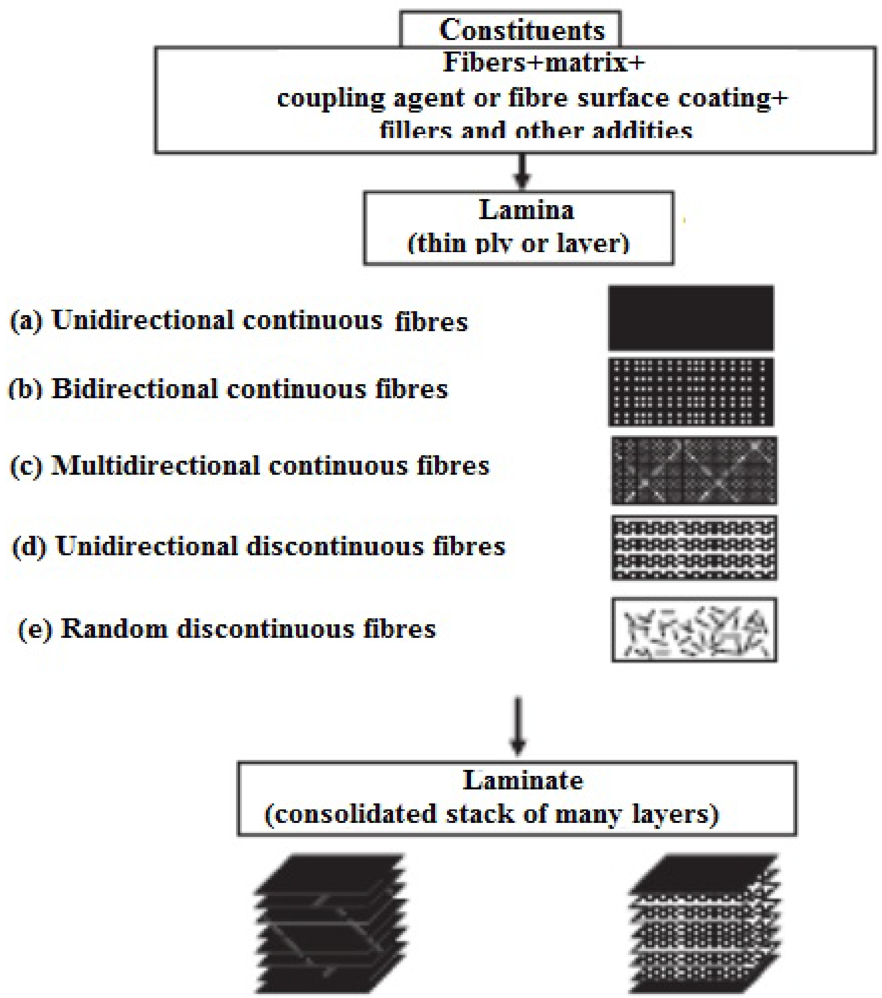


Fig 1.6 Basic building blocks in fiber-reinforced composites [6]

For the present experimental work two layer laminated specimens with 0° fibre orientation have been used.

1.2.9.1 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

1.2.9.3 Applications of laminated composites

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

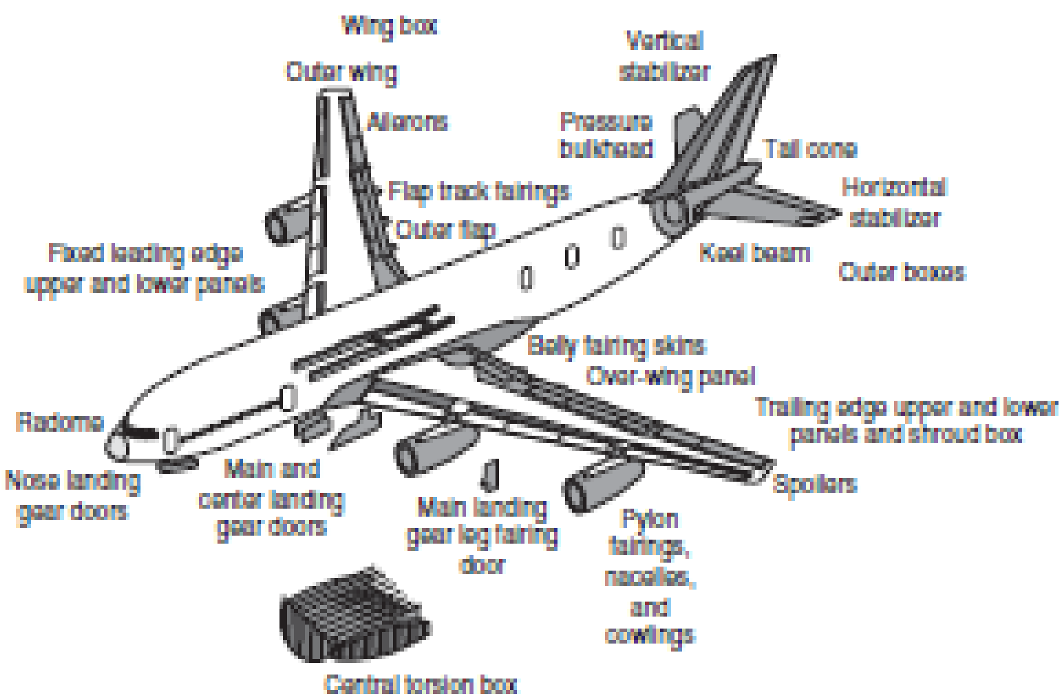


Fig.1.7 (a) Use of fiber-reinforced polymer composites in Airbus 380[6]

1.2.10 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 mold is wetted out with the mixture. The sheets of fibre glass are placed over the mold and rolled down into the mold using steel rollers. The material must be securely attached to the mold; air must not be trapped in between the fibre glass and the mold. 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 mold. Spray-up is an open molding composites fabrication process where resin and reinforcements are sprayed onto a mold. 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 mold.
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.

1.3 Damage in laminated composite

1.3.1 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.

1.3.2 Damage induced due to environmental degradation [6]

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 fiber-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 fiber–matrix interface, which may be followed by diffusion of water or other fluids into this area. In turn, this may cause a reduction in fiber 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, hygro-thermal 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

1.3.3 Damage induced due to working condition

a. Matrix cracking (tensile or shear)
b. Fibre breakage
c. Delamination (ply separation)

a) **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.

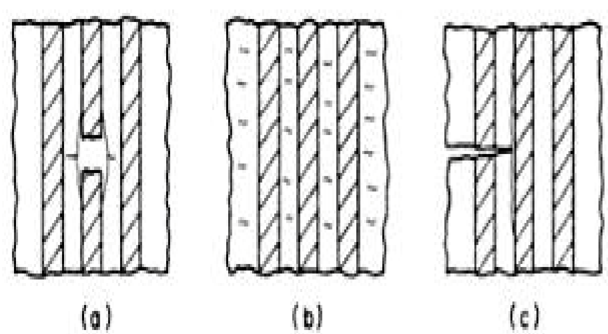


Fig 1.8 (a) Fibre breakage (b) Matrix cracking (c) Interfacial shear failure [8]

b) **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.

c) **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.

Fig. 1.9 Delamination [8]

c) **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.

Fig 1.10 Fibre breakage & pullout [36]

PART-B

1.4 Non-Destructive Testing

The field of Nondestructive 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.

1.4.1 NDT Techniques [8]

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 shadowgraph 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 into a 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.

1.4.2 Comparison of NDT techniques for composite defect detection

Table 1.2 Comparison of NDT techniques for composite defect detection [8]

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

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 potential is still need to be investigated.

1.4.3 Ultrasonics for NDT

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 1.11 gives information about setup of ultrasonic testing in flaw detection.

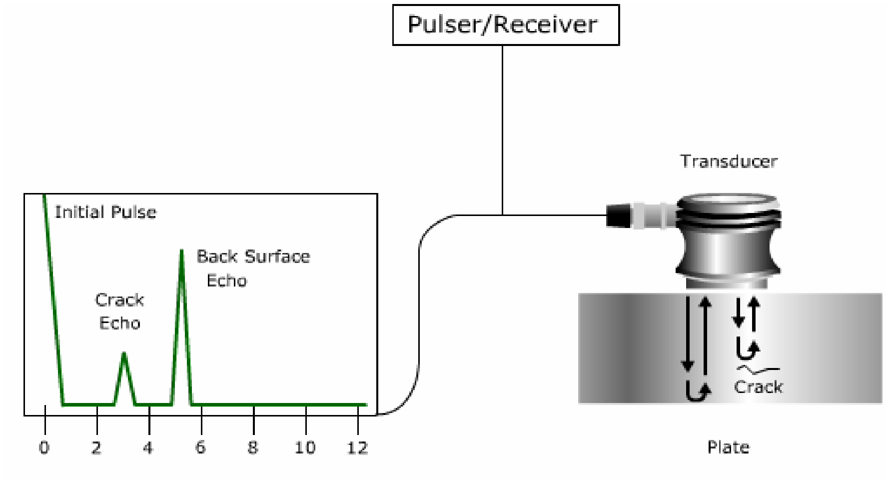


Fig 1.11 Principle of ultrasonic [10]

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.

1.4.4 Modes of wave propagation [10]

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 1.12. 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. 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.

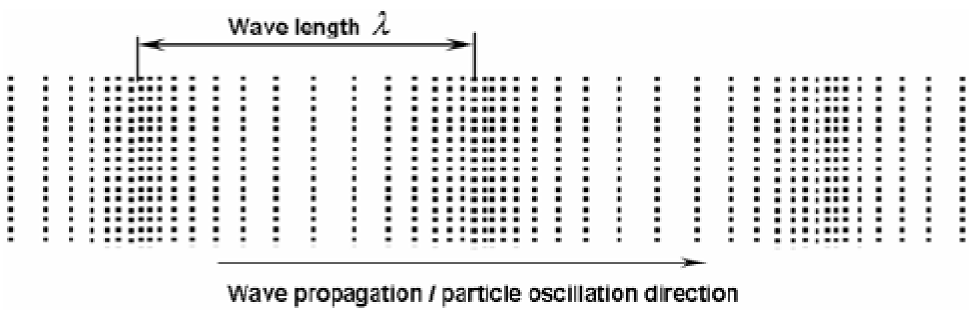


Fig 1.12 Propagation of Longitudinal waves [10]

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 fig 1.13. 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. In fact, 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 neighbour 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.

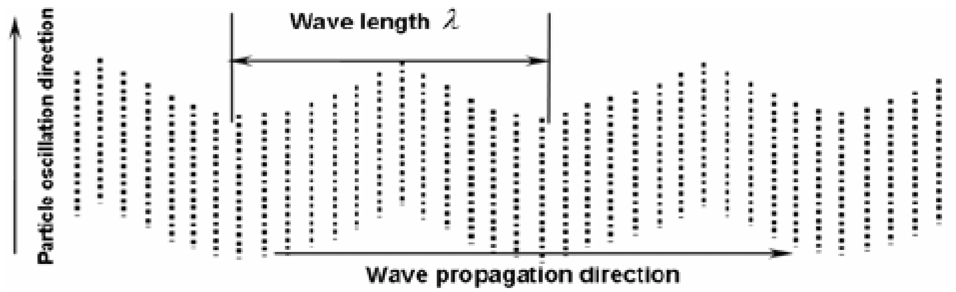


Fig 1.13 Propagation of Transverse waves [11]

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.

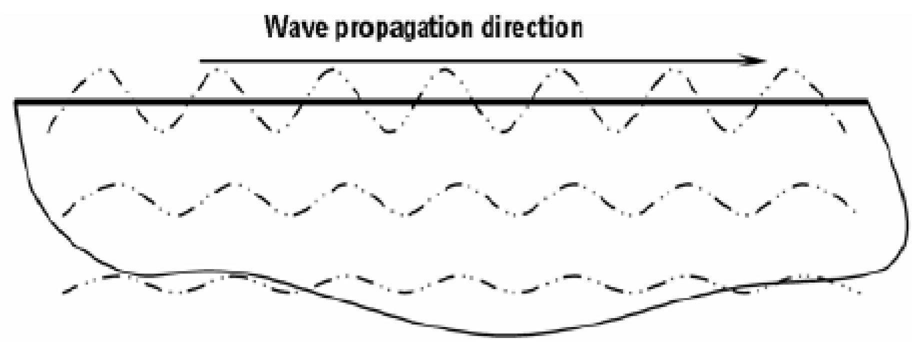
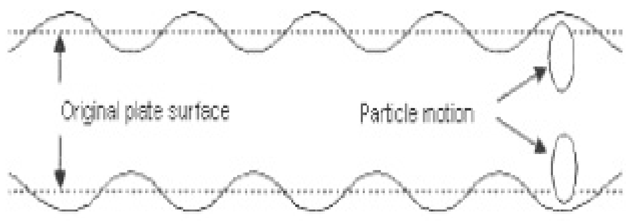


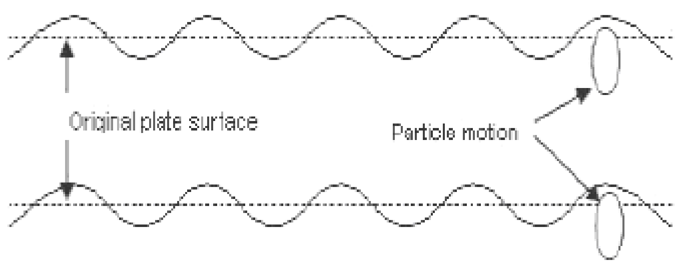
Fig 1.14 Propagation of surface waves [11]

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.



(a)



(b)

Fig. 1.15 Lamb Wave mode (a) Symmetric (S mode) (b) Anti-symmetric (A mode) [11]

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 1.15. 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.

5) Creeping waves

These waves are also called head waves. The behavior 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.

1.4.5 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.

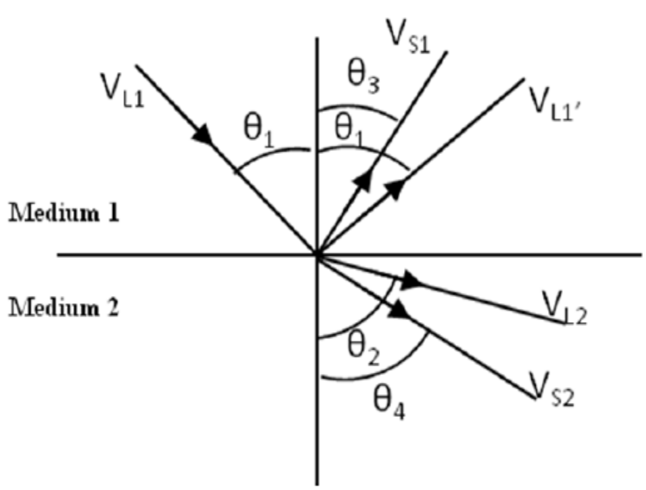
Where:

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.



$$\frac{\sin\theta_1}{V_{L_1}} = \frac{\sin\theta_2}{V_{L_2}} = \frac{\sin\theta_3}{V_{L_3}} = \frac{\sin\theta_4}{V_{L_4}}$$

Fig 1.16 Snell's Law [10]

1.4.6 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

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 1.17. 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.

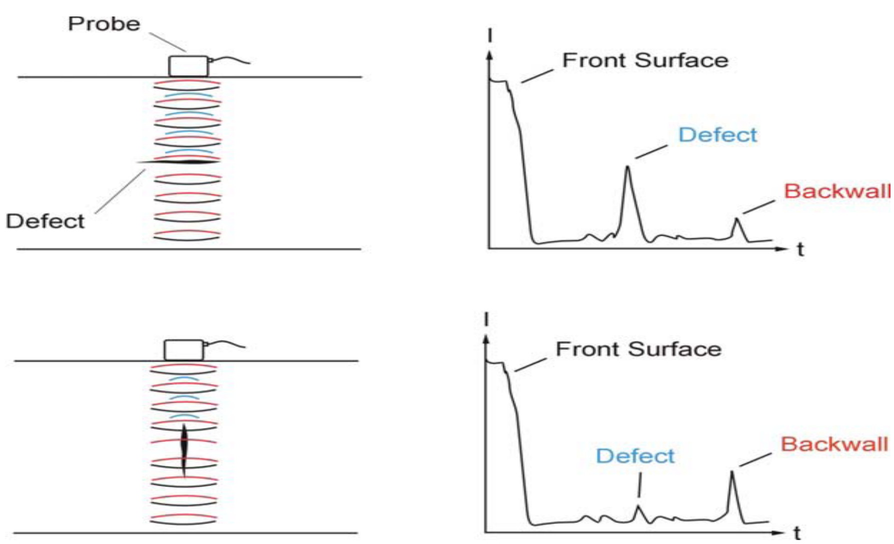


Fig 1.17 Pulse-echo principle [8]

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 Fig 1.18. 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.

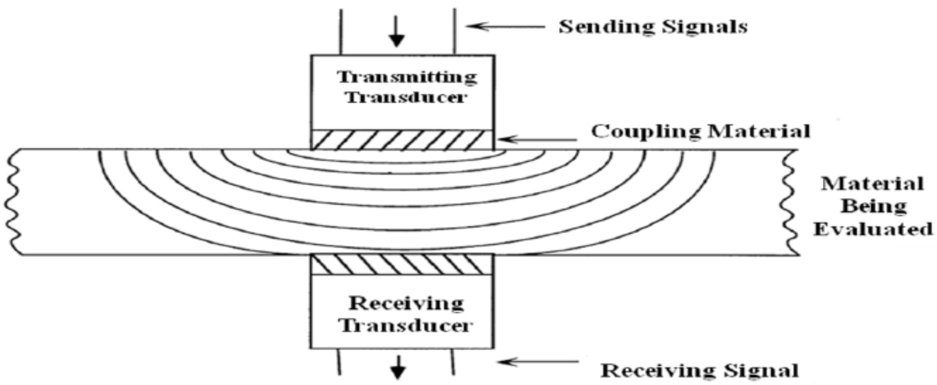


Fig 1.18 Through transmission principle [10]

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 in to 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 ‘twinor T-R probes.

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.

1.4.7 Damage detection in composite plate [11]

Lamb waves are most preferred waves for the ultrasonic testing in damage detection in composite laminate plates, since the lamb waves propagates throughout thickness.

Damage identification techniques using Lamb waves are envisioned to be a promising method in lieu of traditional NDE approaches because Lamb waves feature:

1. The capacity to inspect a large area using few transducers in a sparse configuration
2. The ability to examine the entire cross-sectional area of the structure in terms of multiple wave modes, thereby detecting internal damage as well as surface defects.
3. The capability of classifying various types of damage using different wave modes.
4. High sensitivity to damage and therefore high identification precision.
5. The possibility of inspecting coated or insulated structures such as pipeline under water/ground.
6. The potential for integration with engineered structures and assets for developing online automated damage detection and SHM techniques.
7. Low energy consumption with great cost-effectiveness.
8. But complexity of signal appearance, requiring well-calibrated signal processing and interpretation techniques.

Damage detection & evaluation has been an important area of concern in the design, operation, maintenance and repair of many military and civil naval structures and equipment involving composite structures. Current work proposes to use ultrasonics to monitor damages in the composite utilizing Lamb Waves which subsequently would be made incident on the submerged damaged specimens at varying critical angles. The reflected /scattered signals would be received at particular angles. The variations in the signals received should lead one to identify, locate and evaluate damage and determine the residual life of the subject composite laminated specimens.

1.4.8 Selection of Lamb Wave Modes [14]

The key problem associated with the quantitative measurement of the characteristics of propagating Lamb modes is that more than one mode can exist at any given frequency. Excitation with transducers of finite dimensions inevitably means that all the modes possible at any particular frequency of excitation are produced so it is not possible to separate the modes simply by transforming from the time domain to the frequency domain. Also, since the excitation will not be single frequency, dispersion will also be present leading to complicated time domain signal. Therefore, the time history of the response of the composite plate is usually multi-mode and dispersive. In such cases the shape of the lamp wave packet is strongly dependent on propagation distance. When the wave hits the interface different modes are generated with different velocities and energy. Each mode can be separately excited in the plate using Snell's law. Since velocity of each mode for each frequency will be different, by using Snell's law required mode can be excited in the plate.

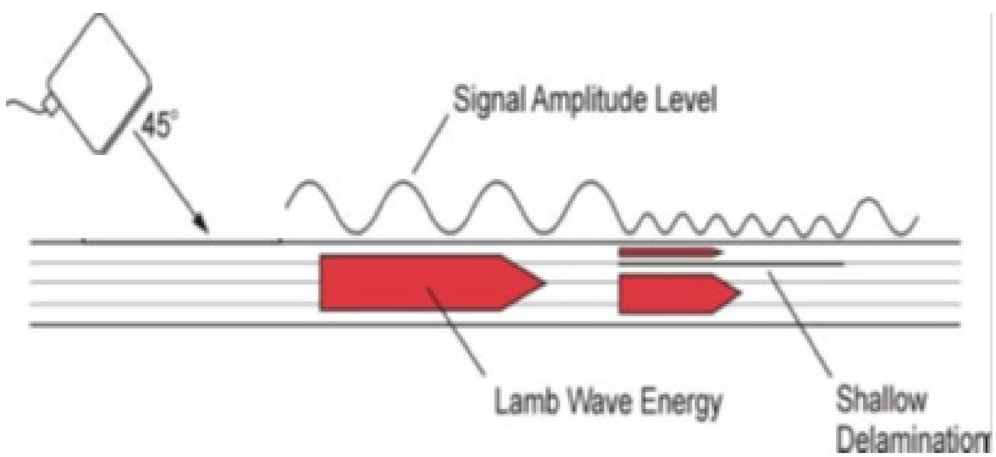


Fig 1.19 Lamb wave interaction near delamination [8]

Different lamb modes detect defects in different layers or plies of multilayered composite. S_0 (zeroth order symmetric) mode is more effective in detecting defects in the central layers of composite because it produces maximum normal stress in those layers. In the presence of the crack, that stress is relieved and hence the signal is significantly affected. On the other hand, A_1 (First-order ant-symmetric) mode produces maximum normal stress in a region between the central plane and the free surface. This mode is more effective in detecting defects in that region.

Closure

This chapter had discussed general introduction about composite material, laminates, their applications, and manufacturing method. Also what type of damage can occur in composites & how Ultrasonic as NDT tool can help in detection & evaluation of these defects has been discussed.

Following chapter deals with previous research work done in the area of damage evaluation in composites with help of ultrasonic testing. Literature survey for last 15 years has been carried out & discussed.

CHAPTER 2 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.

Kundu et al (1998) [14]

Presented study on the guided waves in Multi-layered plates for internal defect detection. He investigated the stress & displacement fields inside a multilayered plate analytically & experimentally. Experiment investigations were carried out on a ceramic composite plate that has 12 plies of fibres going in 0° and 90° directions [0, 90]. The incident angles and frequencies of ultrasonic signal for generating different Lamb wave modes in this plate are obtained experimentally as well as from theory. Displacement and stress fields inside the plate for some of these Lamb wave modes are computed which are used for studying internal damage. Internal stress distribution varies significantly from one lamb mode to other. Hence different lamb modes detect defects in different plates. The Lamb mode that produces maximum stress in a specific layer should be most sensitive for detecting defects in that layer. The stress and displacement inside a 12 layered-anisotropic plate shows that S_0 Lamb mode is more effective in detecting defects in central region(sixth and seventh layers) of plate and A_1 mode is more effective for imaging defects in third, fourth, ninth and tenth layers.

Seale et al (1998) [15]

Presented two studies to monitor fatigue damage and two studies to monitor thermal damage in composites using Lamb waves. In the fatigue studies, the Lamb wave velocity was compared to moduls measurements obtained using strain gage measurements in the first experiment and the velocity is monitored along with the crack density in the second. In the thermal damage studies, one examines samples which were exposed to varying temperatures for three minute duration and the second includes rapid thermal damage in composites by intense laser beams. In all studies, the Lamb wave velocity has demonstrated to be an excellent method to monitor damage in composites. The propagation of Lamb waves depends on a variety of material properties: elastic stiffness constants, density, and thickness. As a material is damaged in some fashion, one or more of these material properties are altered. Since the Lamb wave velocity is directly related to these parameters, an effective tool exists to monitor damage in composites by measuring the velocity of these waves.

Kessler et al (2001) [16]

Presented part of an experimental and analytical survey of candidate methods for in-situ damage detection of composite materials. Results were presented for the optimization of Lamb wave techniques applied to quasi-isotropic graphite/epoxy specimens containing representative damage modes. Linear wave scans were performed on narrow laminated coupons and sandwich beams by monitoring the transmitted waves with piezo-ceramic sensors (PZT). Optimal actuator and sensor configurations were devised through experimentation, and various types of driving signals were explored. Lamb wave techniques have been proven to provide more information about the presence of damage and its severity than previously tested methods, and may prove suitable for structural health monitoring applications since they travel long distances and can be applied with conformable piezoelectric actuators and sensors that require little power.

Kundu et al (2001) [17]

Studied 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. One shortcoming of Lamb wave inspection technique is that in a symmetrically layered composite plate stress and displacement magnitude and energy distribution profiles for all lamb modes are symmetric about the central plane of the plate, hence from Lamb wave generated image one cannot distinguish between the defects in these two layers of mirror symmetry. 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. The incident angle and the signal frequency should be such that they are close to Lamb mode but not exactly on Lamb mode. The lamb mode investigated here show that the nature of asymmetry in the stress field changes in opposite direction as the point moves from one side of Lamb mode curve to other side.

Kessler et al (2002) [18]

Presented an experimental and analytical survey of candidate methods for in-situ damage detection in composite materials. Experimental results are presented for the application of Lamb wave techniques to quasi-isotropic graphite/epoxy test specimens containing representative damage modes, including delamination, transverse ply cracks and through-holes. Linear wave scans were performed on narrow laminated specimens and sandwich beams with various cores by monitoring the transmitted waves with piezo-ceramic sensors (PZT). For the narrow laminates specimens were 25 x 5 cm rectangular [90/±45/0]s quasi-isotropic laminates of the 9AS4/3501-6 graphite/epoxy system, which were clamped on one end. This procedure was carried out for two of each specimen type at the driving frequency of 15 kHz. For sandwich laminates with aluminum core 2 cm thick and tested at 50 kHz. Results shows that lamb waves with low frequency are helpful in detecting damage in thin laminates as compared to sandwich laminate due to core damping.

Sevostianov et al (2003) [19]

Evaluated quantitative characterization of damage accumulation during hydrothermal aging of polymer matrix composites. Effective elastic stiffness and thermal diffusivities of glass fiber reinforced thermoplastic are measured at several steps of aging. Anisotropic damage accumulation is identified. It is shown that both elastic and thermal properties of the composite degenerate with the accumulation of damage. The extents of degenerations are linked to each other using the methods of micromechanics. The established cross-property connections are in a good agreement with the experimental measurements. The ultrasonic evaluation of elastic properties of materials is based on the relationships between elastic stiffness of the material and the phase velocities of the ultrasonic waves. The thermal conductivities were calculated from the thermal diffusivities measured by the flash method (ASTM E 1461-92). It is shown that both elastic and thermal properties of the composite degenerate with the accumulation of damage initiated by the aging.

Hay et al (2003) [20]

Described an experimental technique to locate guided wave modes with potential for rapid inspection of composite skin–honeycomb core structures. Sample dispersion curves for a composite skin–epoxy layer were provided as guidance for practical phase velocity and frequency ranges. The inspection potential at two different phase velocity–frequency operating points were evaluated and compared to conventional ultrasonic c-scan results. While both results compared well, the guided wave excited at 0.5 MHz showed superior sensitivity. The sensitivity difference was explained in terms of the displacement field variation as frequency is swept.

Zhang et al (2004) [21]

Studied non-destructive testing of barely visible impact damage in polymer matrix composites using different NDT techniques visual inspection, ultrasonic C-scan, electronic speckle pattern interometry (ESPI),electronic shearography(ES) and optical deformation and strain measurement system(ODSMS).Internal damage was introduced using an instrumented falling weight impact test machine. It was found that different NDT techniques were successful in identifying & visualize the impact internal damage. For ultrasonic component under study was placed in water tank. Flaws in material reflected or scattered part of the incident energy in a different way compared neighboring locations, leading to differences in amplitude and time of flight. The differences were picked up by the probe, computed and internal damage was visualized.

Demcenko et al (2005) [22]

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 delamination position influence on the Lamb wave propagation velocity is investigated experimentally and numerically. 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. The loss of information occurs using the air-coupled ultrasonic technique due a mode conversion phenomenon in defective areas. In our case the A0 Lamb wave mode generates the S0 Lamb wave mode, which in a low frequency range has too low energy leakage into air and due to this it cannot be detected with the air-coupled ultrasonic technique. When the test object is optically reflective this disadvantage can be solved using laser interferometer as a receiver. If the material is not absorbing water or other liquids the immersion ultrasonic technique can be applied for investigations.

Edalati et al (2005) [23]

Presented Defects Evaluation in Lamb Wave Testing of Thin Plates of aluminum.Two ultrasonic lamb wave techniques, pulse-echo (a1 mode) and emission (s1 mode) were used for interpretation of notch defects. It was found that amplitude analysis can give some qualitative and quantitative information about defects depth.In this respect, pulse echo method resulted in better sensitivity of amplitude to defects depth and distance variations as compared to emission method. Amplitude analysis showed that defect depth could be evaluated by drawing the DAC curves. 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.

Zhang et al (2006) [24]

Presented a global matrix model, developed on Nayfeh's transfer matrix technique. The method provides an alternative to the transfer matrix technique and can be used on plate systems of any numbers of layers of different materials and thickness. Study concentrate on the effect of fiber orientation on Lamb wave propagation in layered anisotropic composites plates because plate structures with various degrees of macroscopic anisotropy are often encountered in the study of composite materials. The calculated dispersion curves for various fiber orientations were presented together with plots of the through thickness particle stress component amplitudes for two fundamental modes a0 and s0. The numerical examples provide the rich characteristics of Lamb waves in anisotropic layered plates.

Wrobel et al (2006) [25]

Presented study to find relationship between the ultrasonic wave velocity or attenuation coefficient and the local fiber content in glass/polyester composites. Experimental data have been obtained using ultrasonic wave velocity and attenuation measurements. To determine the actual fiber content in the composites, the standard destructive analysis was applied. For ultrasonic nondestructive testing, through-transmission technique was used. In the study, ultrasonic testing and standard damage analysis were carried out on the two groups of glass/polyester specimens, which were fabricated by conventional hand lay-up.The specimens were prepared with variation of reinforcement content. Results obtained from non-destructive analysis have proven a possibility that the propagating velocity of an ultrasonic wave can be the primary parameter in evaluation of the glass content in a glass/polyester composite material. The obtained results showed that increasing fiber content leads to an increase in ultrasonic wave velocity. The determined relationships are linear functions, different for each type of reinforcement.

Berketis et al (2007) [26]

Evaluated the effectiveness of traditional water coupled and non-contact ultrasonic C-Scan systems for wet damaged Glass Fiber Reinforced Polymer (GFRP) composites. Long term immersion for up to 24 months, of impact damaged GFRP plates in hot water at 65º C and 93º C causes serious matrix degradation. Water diffusion is followed by water uptake measurements. The use of water coupled pulse-echo ultrasonic proved ineffective after long-term water immersion as damaged areas become ultrasound-invisible. The use of air-coupled through thickness ultrasonic is examined for damage detection and evaluation. Calibrating the system to a dry condition specimen, a good qualitative and quantitative indication of the degraded state of specimens was obtained. A set of ceramic transducer probes with nominal frequency at 400 kHz were used. The maximum pulse voltage can reach 800 V.

Su et al (2007) [27]

Upon comparative evaluation of the performance of forward and inverse inferences for damage identification, a data fusion scheme was developed for predicting multi-damage in a structure with the aid of a sensor network. The approach, conducted hierarchically by activating different sensors in a sensor network, fused an extracted signal feature, time-of-flight (ToF), at different levels, to provide an overall consensus as to all possible instances of damage. This consensus was presented in an intuitional contour map indicating the probability of damage occurrence. Benefiting from the sensor network, the dependence of identification processes on a specific sensor was minimized, and the need for interpreting complex signal scattering by multi-damage was avoided as much as possible. To facilitate the extraction of ToF from raw signals, a signal processing approach, scale-averaged wavelet power (SAP) analysis, was introduced. As validation, the proposed identification scheme was employed to gauge dual delamination in a CF/EP woven laminate with a built-in active piezoelectric sensor network. The results have demonstrated the excellent capability of the approach in evaluating multiple structural damage sites.

Xue Qi et al (2008) [28]

Ultrasonic guided waves are used to detect the delamination between skin and honeycomb of a composite helicopter rotor blade. Theoretical work is carried out for guided waves in the trailing edge of a rotor blade, which is a multilayer composite skin/NOMEX half space structure. The dispersion relation is obtained with the global matrix method. Theoretically driven experiments are conducted on a composite rotor blade section to illustrate the effect of delamination to through transmission ultrasonic energy. Both leaky waves and non-leaky wave were considered. The non-leaky wave is suitable for surface damage detection because it concentrates energy on the top surface. However, it is not so sensitive to the skin-substrate de-bonding.

Raisutis et al (2008) [29]

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. From the ultrasonically obtained images it is possible to recognize the geometry of defects and to estimate approximate dimensions of the defects.

Wrobel (2009) [30]

Evaluated the finite elements model for simulation of acoustic wave propagation process in polymer material in the aspect of diagnostic of fatigue changes. Flat model was composed from finite elements with elastic properties of represented medium. Procedure of model modification corresponding with material fatigue degradation was presented. Acoustic and strength characteristics achieved as a result of numerical analysis gave the basis of numerical diagnostic of degradation process. Phase velocities of ultrasound longitudinal wave front propagation in modeled body were evaluated on the basis of analysis. Results are- fatigue degradation of material may be modeled by introducing discontinuities into composite physical model through random removal of finite elements. The result of such procedure is the decrease acoustic wave propagation velocity what is observed also experimentally.

Nadella et al (2010) [31]

Presented a theoretical model based on three dimensional elasticity to characterize guided wave excitation by finite-dimensional transducers in composite laminates. The theory uses an eigen basis expansion for a bulk transversely isotropic material combined with Fourier transforms, the global matrix approach, and residue theory to find the displacement field excited by an arbitrarily shaped finite dimensional transducer. Experimental results obtained in a cross-ply composite laminate are used to assess the accuracy of the theoretical solution.

2.1 Gaps in literature review

Following gaps were found in literature review:-

1. Damage evaluation using ultrasonic guided waves in laminated composites exposed to hygro-thermal loading have not been reported in the literature.
2. Work has not been employed for damage detection in thin laminate composite using ultrasonic guided waves.
3. The laminated composites subjected to bending and tensile pre-loads & relating the loss in strength with ultrasonic signal have not been reported in literature.
4. Delamination detection & evaluation in laminated composites using ultrasonic guided wave is still an area need to be explored properly.

CHAPTER 3 OBJECTIVES OF PROPOSED 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 and inclusions. Their effect on the overall structural integrity of the component may be serious.

Damage and general material degradation can also occur during the in-service operation of composite components. Typical causes may be due to environmental degradation or due to different work-loading conditions such as tensile loading, compressive loading, cyclic loading or impact loading resulting in delamination, matrix cracking, fibre breakage etc.

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 characterization. Lamb wave propagation provides an effective solution for damage detection in thin laminate composites.

Based upon the literature survey related to damage in glass fibre composite laminate, overall objectives of the present study can be listed as:

1. Generate and investigate the propagation of ultrasonic waves through the composite laminates subjected to environmental degradation and/or seeded with commonly occurring defects in composite laminate.
2. Characterize various damages in composite laminates and its extent through the analysis and comparison of wave signatures of healthy and damaged composite specimens.
3. Study of wave characteristics through composite laminate which give relationship between different loading conditions & extent of damage. This will help in predicting useful life of composite parts without catastrophic failure.

CHAPTER 4 EXPERIMENTAL DETAILS

4.1 Introduction

This chapter discusses the size & specifications of various specimens, their fabrication procedure & the experimental setup required to carry-out the proposed work given in the previous chapter. Various machines & equipment used to carry out destructive & non-destructive testing of specimen have been discussed.

4.2 GFRP laminates specifications/dimensions

The specifications/dimensions has been set according to the respective experimental study which has been discussed below

4.2.1 Specimens for hygro-thermal study

Glass fibre sheets have been used for making specimen. Laminate specimens have two layers of glass fibre & were placed along 0° orientation side for laying the specimens. ASTM standard D3037/3039 and D790 have been used to decide the specifications of tensile and bending specimen. The dimensions of specimens are shown in Fig. below

- **For tensile testing**

Length of the specimen	:	500mm
Width of the specimen	:	15mm
Thickness of the specimen	:	4mm

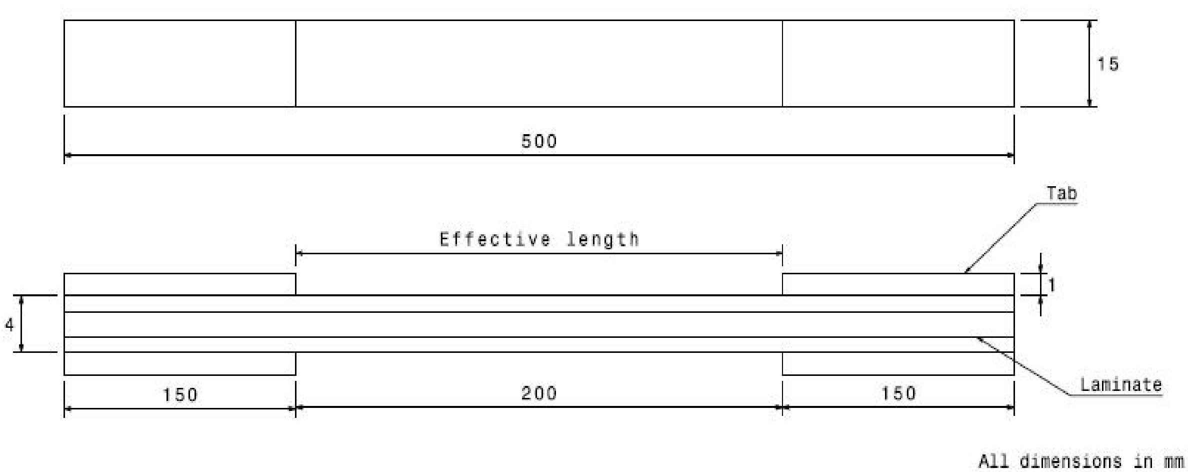


Fig. 4.1 Tensile specimen for hygro-thermal study

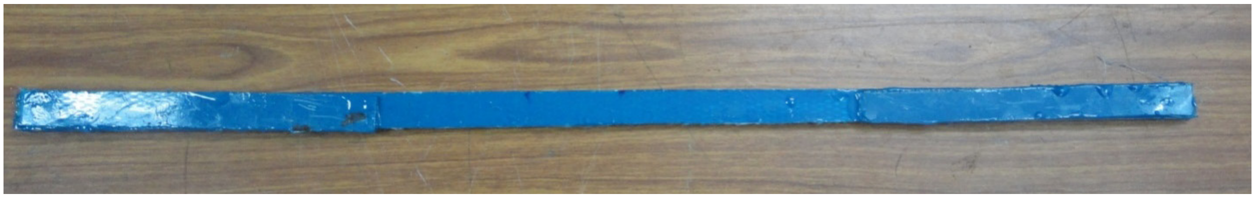


Fig. 4.2 Actual Tensile specimen

- **For bending test**

Length of the specimen : 125mm

Width of the specimen : 12.7mm

Thickness of the specimen : 4mm

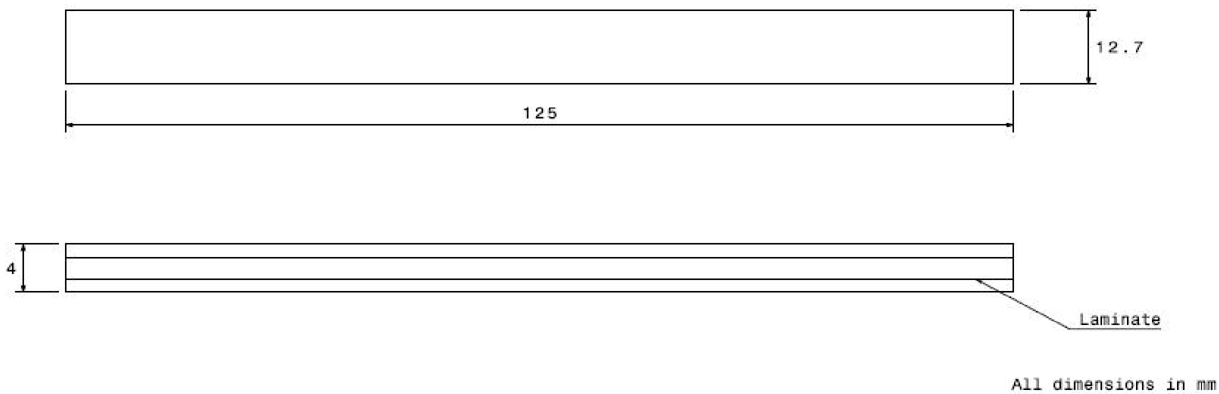


Fig. 4.3 Bending specimen for hygro-thermal study

Fig. 4.4 Actual bending specimen

- **For Ultrasonic test**

Length of the specimen : 300mm

Width of the specimen : 80mm

Thickness of the specimen : 4mm

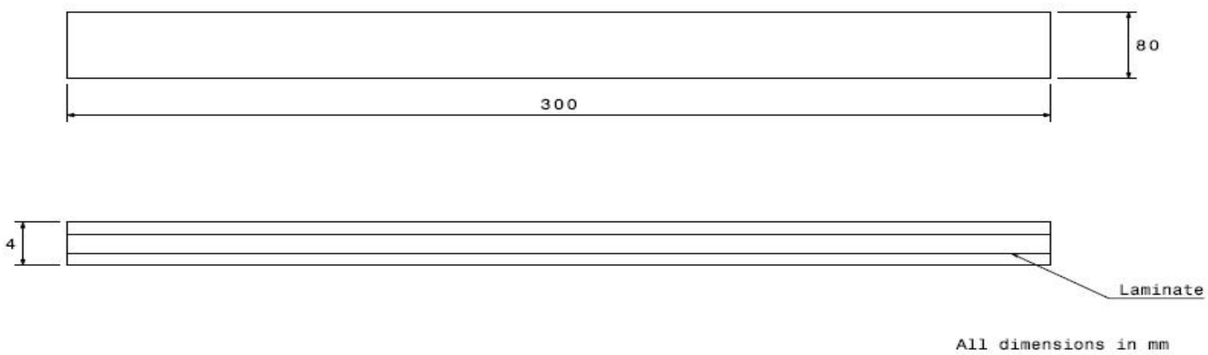


Fig. 4.5 Ultrasonic testing specimen

4.2.2 Specimens for mechanical damage study

Glass fibre sheets have been used for making specimen. Laminate specimens have two layers of glass fibre & were placed along 0° orientation side for laying the specimens. Specimens are same as of Hygro-thermal tensile loading but the width of specimens is more than the ultrasonic transducer diameter to avoid the boundary effect.

Length of the specimen	:	500mm
Width of the specimen	:	40mm
Thickness of the specimen	:	4mm

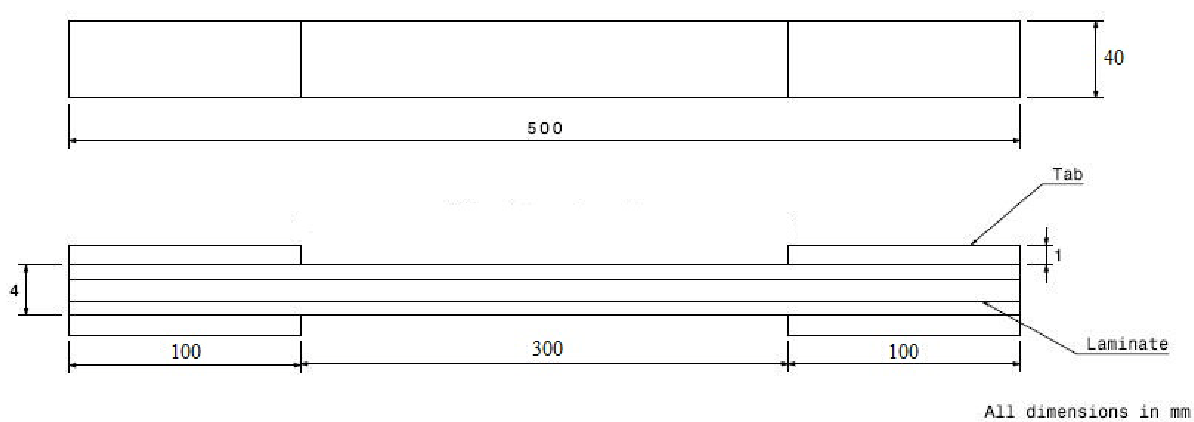


Fig. 4.6 Specimen for mechanical damage study

4.2.3 Specimens for simulated delamination study

Two type of delamination has been put into specimens to study delamination effect. One was of varying extent & other was by varying depth i. e in between different layers. For varying extent delamination, two layers (glass fibre) laminate has been fabricated & for varying depth delamination, three layers (glass fibre) unidirectional laminate has been fabricated.

- **Delamination of varying extent**

  Length of the specimen : 300mm

  Width of the specimen : 100mm

  Thickness of the specimen : 4mm

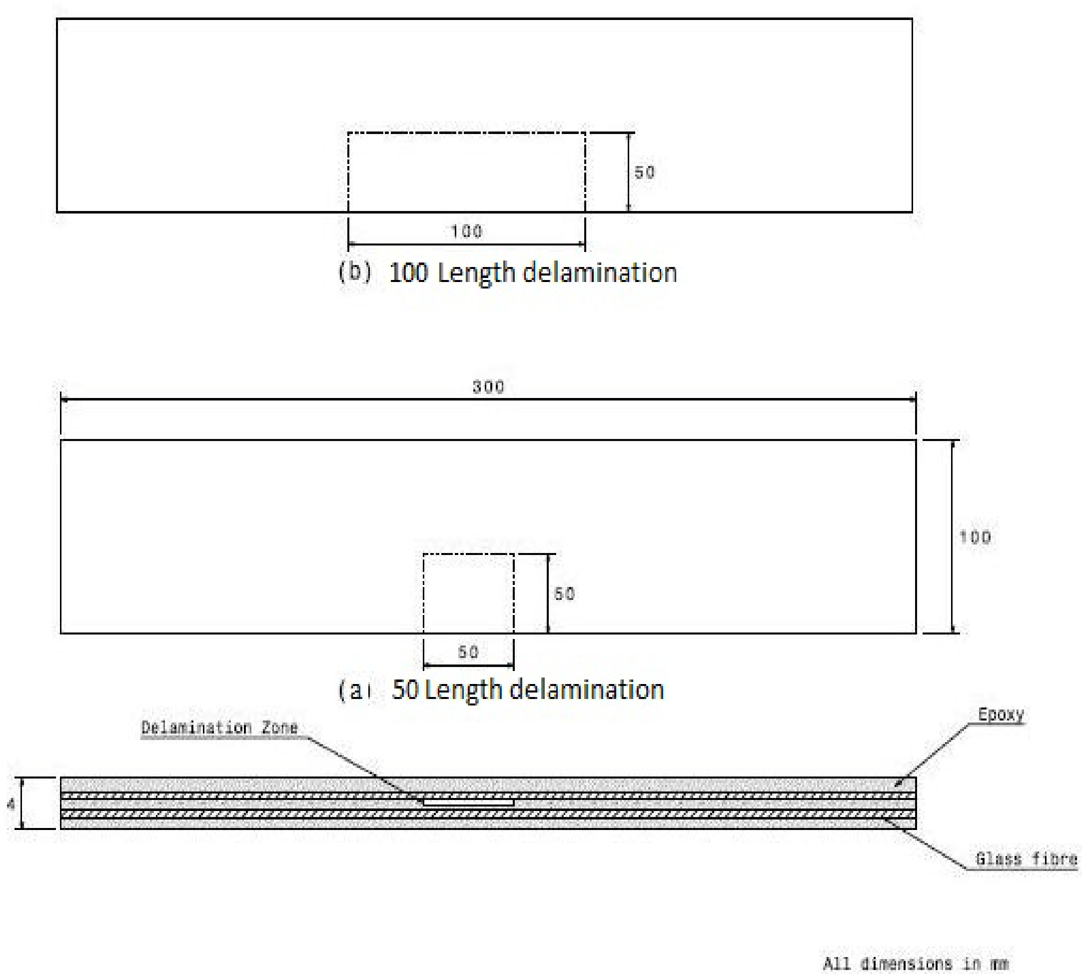


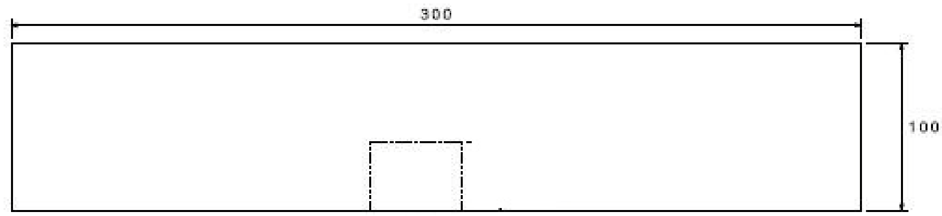
Fig. 4.7 Specimen with simulated delamination damage of varying extent

- **Delamination of varying depth**

  Length of the specimen : 300mm

  Width of the specimen : 100mm

  Thickness of the specimen : 5mm



(a) 100 Length delamination

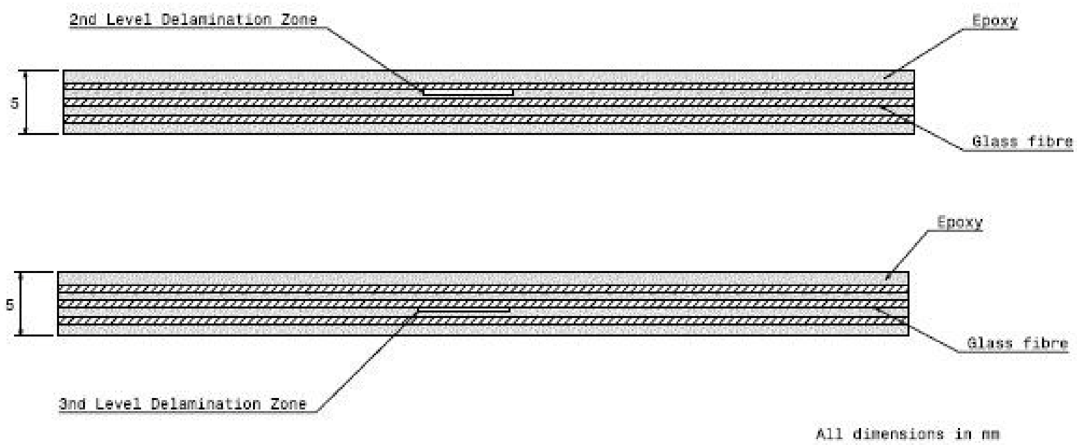


Fig. 4.8 Specimen with simulated delamination damage at varying depth locations

4.3 Specimens Fabrication

Fabrication of laminated specimens required for testing as per the dimensions mentioned earlier included following procedural steps.

4.3.1 Material procurement

Following material has been procured from BASF construction chemicals (India) private limited.

- E-Glass 900 gsm unidirectional glass fibre sheet roll(width 50 cm)
- MBrace Epoxy & hardener

4.3.2 Cutting GFRP Sheet

Glass fibre sheet of required size according to the standard discussed above was cut from roll of GFRP. The sheets were initially cut 50mm more than actual sample length. The reason for overcutting was that after laminated specimen has been fabricated & cured, extra edges were trimmed in order to remove flaws after layup operation.

Fig. 4.9 Cutting of glass fibre sheet as per size

4.3.3 Mixing of Epoxy

The GFRP sheets have been epoxy coated in order to make a composite material laminate. Epoxy resin basically consists of two parts

a) Base

b) Hardener

Fig. 4.10 Hardener and Epoxy

Fig. 4.11 Mixing of Epoxy and Hardener

Base is thick blue liquid which is considered as main ingredient and orangish coloured hardener is added to it to help it in settling down by starting the exothermic reactions. Both base and hardener has been mixed (by weight) in a container in ratio of 10: 4 respectively.

After putting the base and hardener in required quantity, the mixture was stirred continuously by manual process so that the mixing takes place in proper manner. If mixing has not done properly, the material would not settle well. Also if the ratio of the hardener was more than the pot life of the material would have been lesser. It is important to mention that if the prepared amount epoxy resin was not consumed in 20-30 minute, then epoxy would have settled in container itself. Approximately 300gms of epoxy was needed to apply to both side of the sheet of given specimen.

4.3.4 Applying resin on sheet

The epoxy was applied on sheet using a steel scrapper as shown in Fig.4.12 by carefully spreading it evenly on all sides of sheet. It was made sure that there was no air bubbles entrapped inside the epoxy applied on sheet otherwise it can lead to formation of manufacturing flaw there.

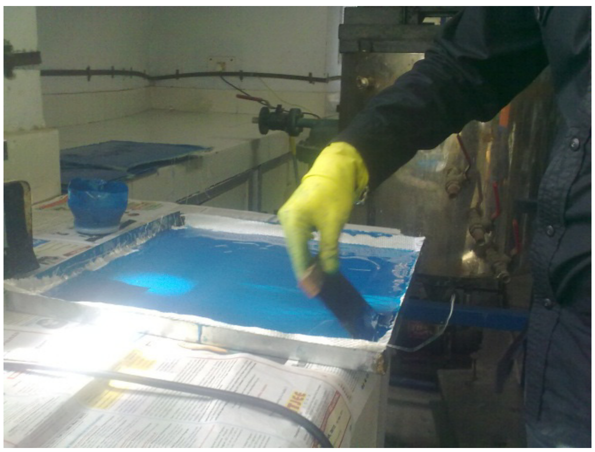


Fig 4.12 Applying resin on sheet **Fig 4.13** After resin application

After that step another sheet has been placed in same direction (0° orientation) and once again epoxy coating has been applied to create a laminated sheet. Finally prepared laminate specimen consists of three epoxy layers & two glass fibre sheets in between them. The full curing of sheet has been done under ambient temperature for at least seven days using it for further testing.

4.3.5 Sizing of sheet for final specimen and tabs

Once the specimens were fully cured, they were cut to actual specimen size using the circular saw machine shown in Fig.4.14 which would cut it into required size of according to given standards. After obtaining the long cured strips of the resin coated FRP sheets, the tensile specimen were further tabbed on each side of either ends as per standard. The tabs were cut in size of 150mm x 15mm with Treadle shearing machine shown in Fig.4.15.


Fig. 4.14 Circular saw **Fig. 4.15** Treadle shearing machine

4.3.6 Placing of tabs on specimen

The Tensile specimen had to be tabbed on either side on two ends to avoid failure at jaw location. For this tabs were cut from sheet which was coated on one side. These tabs were pasted on the tensile specimens with help of epoxy. Paper clips were used to hold tabs in position. Once specimens has been fully cured (after 5 days), paper clips were removed & laminated specimens has been ready for testing

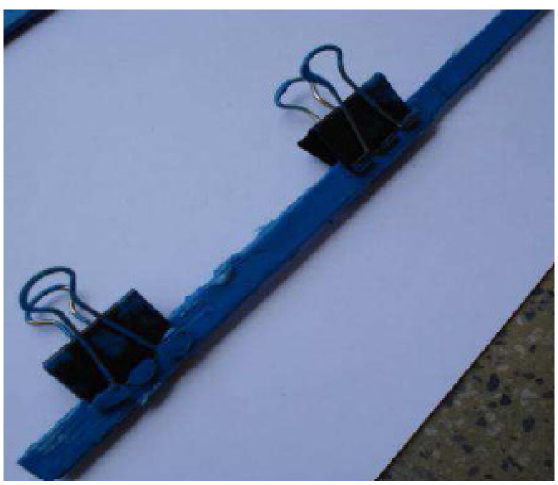



Fig. 4.16 Placing of tabs **Fig. 4.17**Tensile tabbed specimen

4.4 Experimental setup

The various experimental setups & testing machine used for experimentation as discussed below

- Ultrasonic/ Non-destructive testing setup
- Hygro-thermal loading setup
- Mechanical/Destructive testing setup

4.4.1 Ultrasonic/Non-destructive testing setup

The experimental setup consists of pulser/receiver which generates the pulses for every 5 ns. This is sent to the transducer which converts the pulse to mechanical wave. 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. Testing is done in water as compared to air because water acts as good couplant.

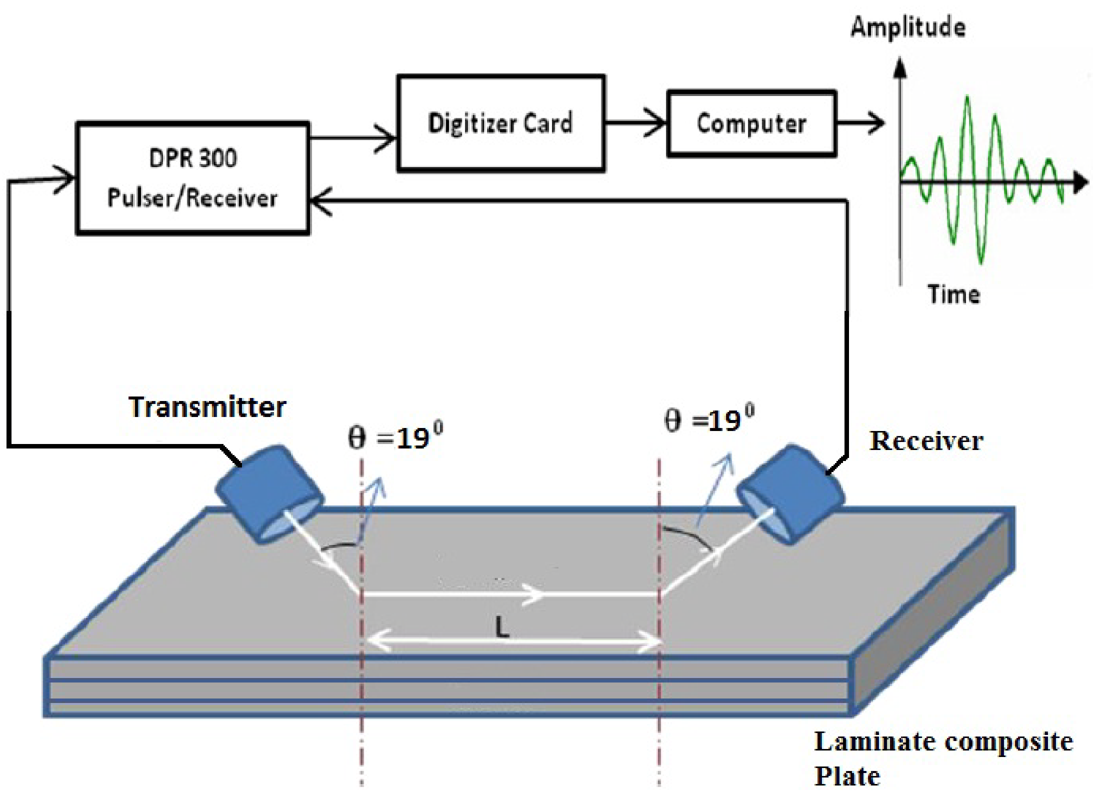


Fig. 4.18 Ultrasonic experimental setup for testing in water

A) 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) and 1 MHz (0.5" diameter) has been used as shown in fig. 4.19.

(a) (b)

Fig. 4.19 Immersion probes (a) 0.5 MHz (b) 1 MHz

B) 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

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.

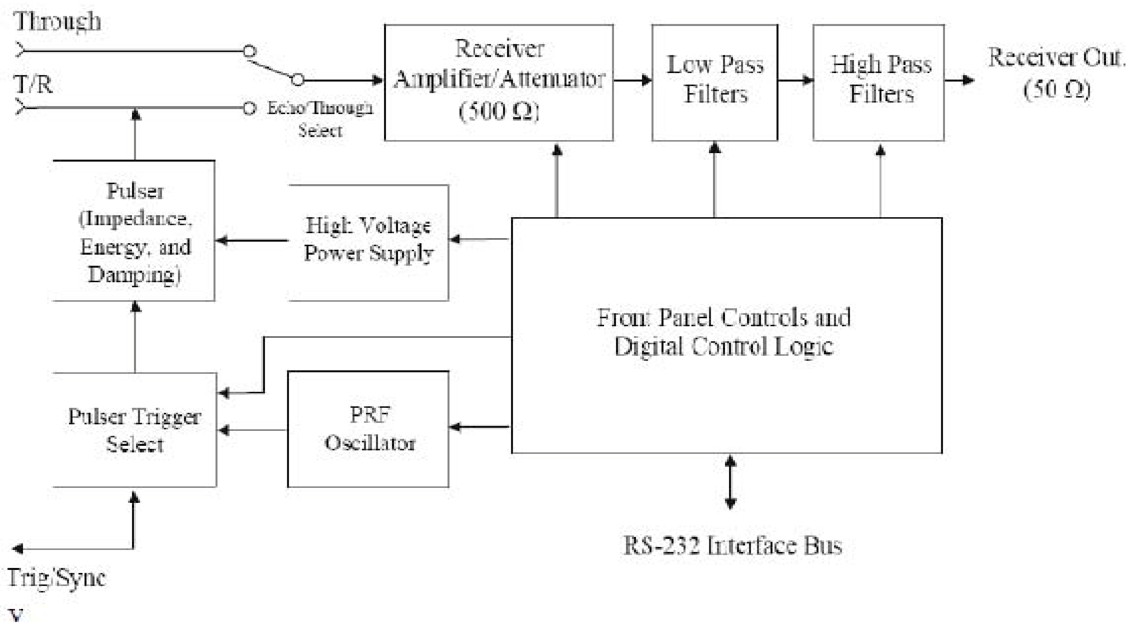


Fig. 4.20 Layout of JSR Pulse Generator

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.

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.

Table 4.1: Configuration of JSR Pulse Generator

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

C) 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.

Fig. 4.21 JSR Pulse Generator

Table 4.2: Configuration of Digitizer Card

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 Ω± 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 pk-pk
Impedance	50 Ω

D) Four axis- scanning set up

In this testing, an acrylic tank of size (120cm) x (72cm) x (50cm) and set up to move and set the transducers at a given angle has been used for testing as shown in the Fig.4.22

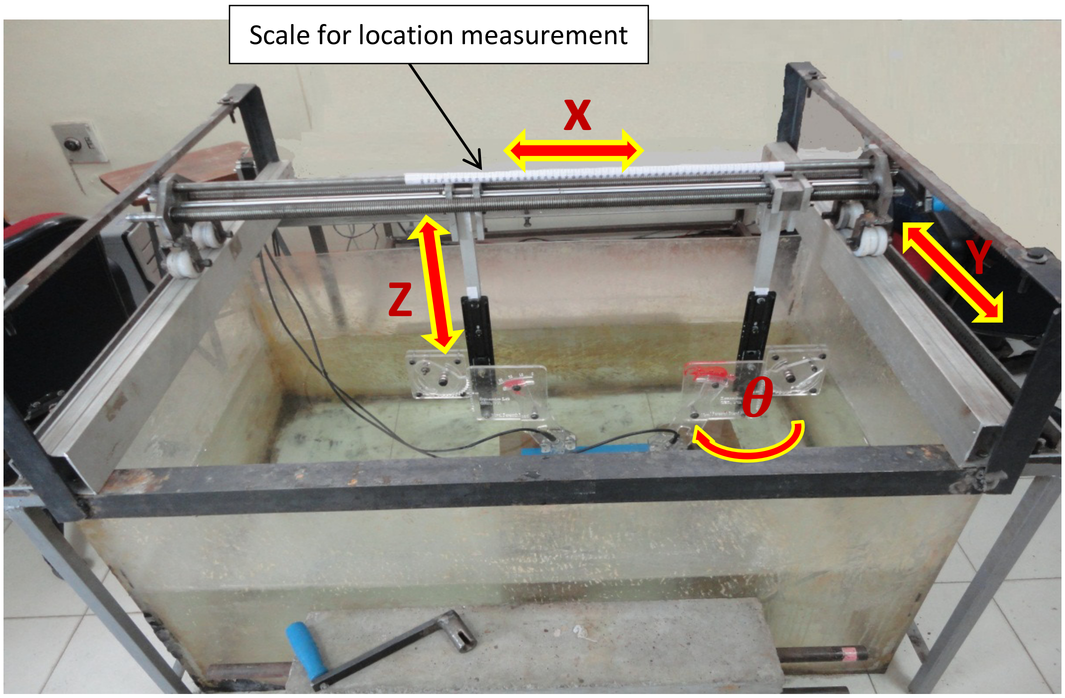


Fig. 4.22 4-Axis scanning set up

This set up 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 0-30 degree.

4.4.1.1 Ultrasonic Testing of Composite plates in Water

The plate and the transducers are immersed in water where water becomes couplant for the transducer to send ultrasonic waves in the plate. In this the transducers were kept at an angle to the surface of the plate. For generating different modes, the incident angles were changed. The study has been carried out on different composite laminated specimens.

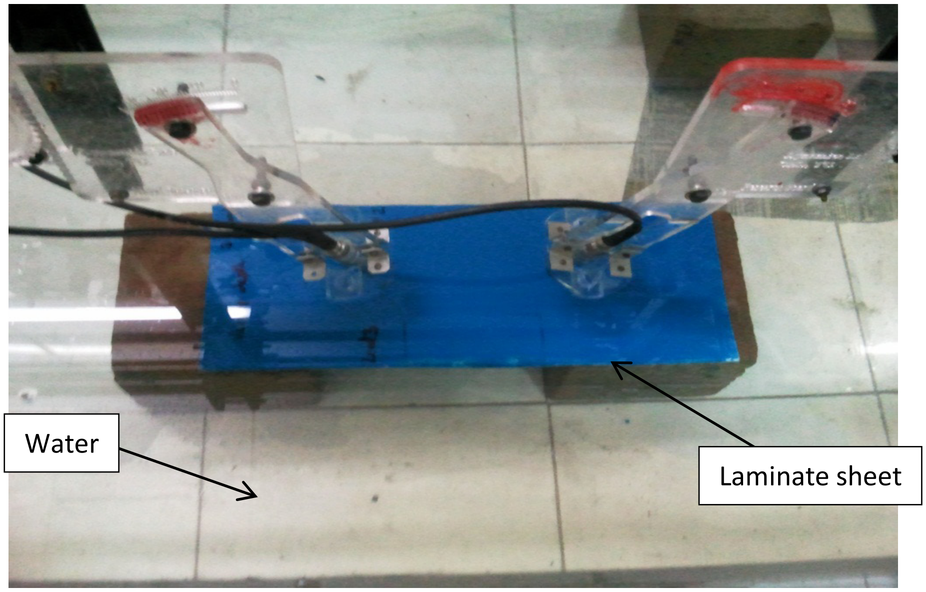


Fig. 4.23 Ultrasonic testing of plates in water

4.4.1.2 Selection of the Frequency & Angle for damage detection

Transducers with central frequencies of 0.5 MHz and 1 MHz have been used for the experiments. Higher frequencies were 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 we have adopted the approach of finding the particular mode which is helpful for detecting the particular type of damage (delamination, hygro-thermal stresses, and mechanical loading stresses) by testing the plate at various angles. The angle which is particularly suitable to find particular damage more appreciably has been then selected. This process has been done at both frequencies i.e. 0.5 MHz & 1 MHz .Then angle was fixed for that damage & through transmission signal scanning has been done over laminate plate to check the delamination or 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.

4.4.2 Hygro-Thermal loading Setup

An experimental setup shown in Fig.4.24 has been prepared to carryout accelerated aging tests in order to evaluate the performance of GFRP laminated specimen in extreme conditions. The field environment similar to tropical climate (i.e. aqueous at 45° C) had been simulated using this setup.

Fig. 4.24 Hygro-thermal Experimental setup

The GFRP samples made to the specifications were immersed in two baths containing NaOH solution (5% concentration by weight) & water for different time durations (up to 30 days) & maintained at constant 45°C temperature throughout the exposure. The specimens were removed from the bath after decided time period (15 & 30 days). The tensile & bending strength was evaluated and Ultrasonic signal was taken to relate the decrease in strength to loss in ultrasonic signal which helps to check the health of composite laminate specimens.

4.2.2.1 Setup fabrication

Setup shown in Fig. 4.24 basically consists of

1. Two water baths.
2. Heating element.
3. RTD sensor.
4. Temperature controller.
5. Solid state relay

1) Water Baths

Experimental setup consists of two well insulated tanks as shown in Fig. 4.25-26. The tanks are made up of plastic. The approximate capacity of the NaOH tank is 60 litres. One tank is filled totally with tap water and second tank has solution of aqueous NaOH solution with 5% strength by weight. Both tanks were kept at same temperature i.e. 45°C. Makeup arrangement due to evaporation of water was employed.

Fig. 4.25 NaOH tank (at 45°C)

Fig. 4.26 Water tank (at 45°C)

2) Heating element

The setup temperature is maintained with the help of heating rod of wattage 1000 kW connected via temperature controller with single phase connection. As temperature reaches to required value the power supply of rod is cut off by temperature controller.

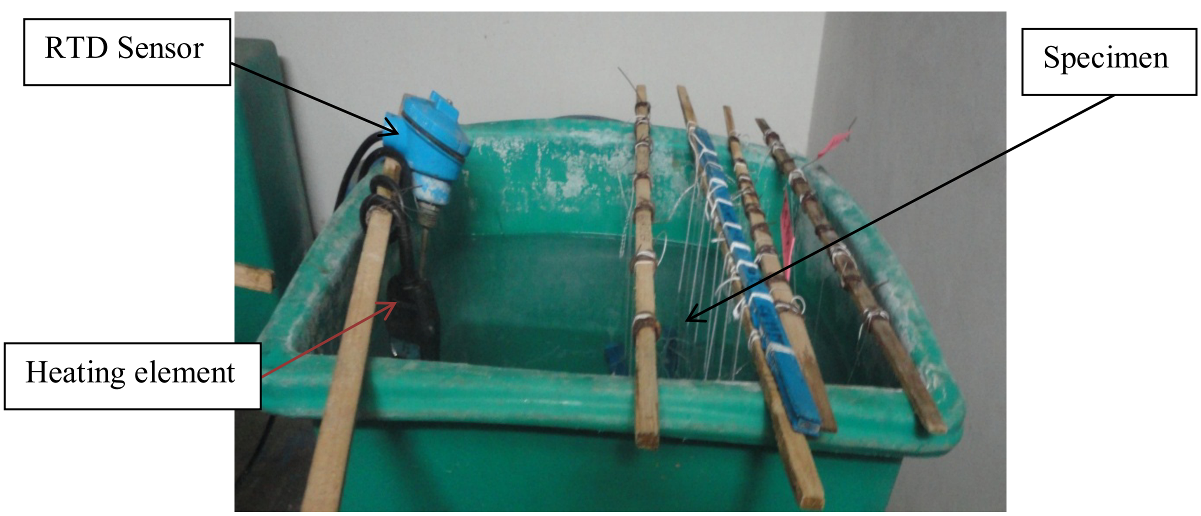


Fig. 4.27 Heating Element and RTD sensor

3) RTD (Resistance Temperature Detector) sensor

Both baths are provided with RTD sensor as shown in Fig.4.27. It senses temperature of water bath at given time and input is sent to the controller which controls temperature of the system as per set value.

4) Temperature controller:

For thermal aging of specimen the water bath is maintained at specified temperature by temperature controller. Temperature controller is connected with the bath along with relay cutoff as shown in Fig. 4.31.

Proportional-integral-derivative (PID) control is used to maintain the temperature. On the controller display feed the "Set Value" of temperature indicated in green and the "Process Value" of temperature would be indicated in the red, which is the output from the RTD sensor. First time the controller is set to auto-tune mode so that it could adjust itself according to the input variables. Once the bath had attained the set value the controller cuts off its supply and after sometime it senses the temperature had gone below set value it again starts heating to obtain set value.

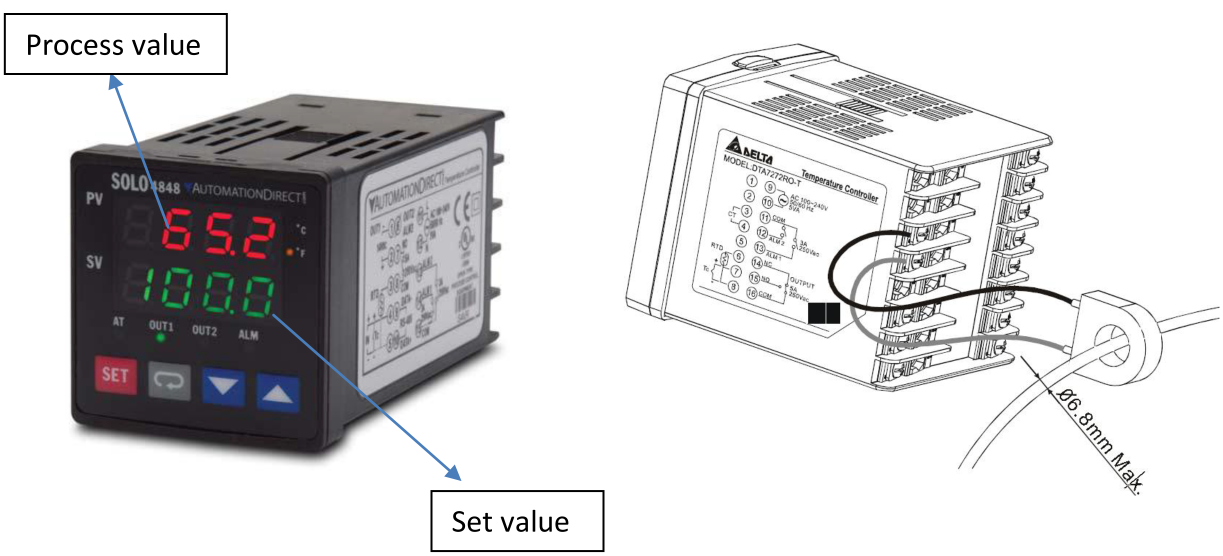
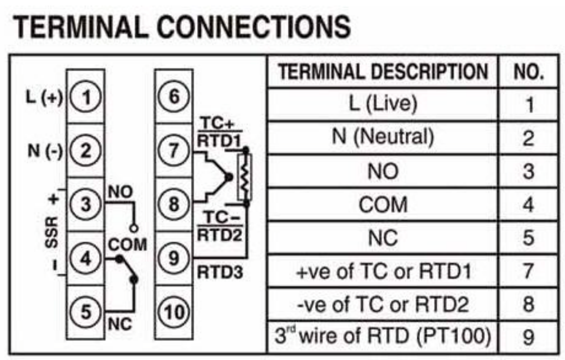


Fig. 4.28 Actual image of the temperature controller showing front and back side [41]

The connections of controller are shown below in the Fig.4.29 as given by its manufacturer. It consists of terminals named with different numbers. Each terminal is having specific input or output requirements. Terminal 1 and 2 are connected to the power supply of 220Volts with live at 1 and neutral at 2. The relay is connected to the terminals at 3 & 4 with respective positive and negative connections. The live terminal of the heating element is connected to the T1 terminal of the relay and neutral is connected to the power input. The RTD Sensor is connected to the terminals 7, 8 & 9 as shown in circuit diagram.



TERMINAL DESCRIPTION	NO.
L (Live)	1
N (Neutral)	2
NO	3
COM	4
NC	5
+ve of TC or RTD1	7
-ve of TC or RTD2	8
3rd wire of RTD (PT100)	9

Fig. 4.29 Circuit diagram of connections [41]

Fig. 4.30 Temperature display panel [41]

5) Solid State Relays (SSR)

The solid state relay shown in Fig.4.31 is required to break the circuit in case of overloading. It controlled the switching of the heating element and acted as a switch. It helps in protecting controller for any kind of overload or short circuiting.

Fig. 4.31 Solid state relay [41]

4.4.3. Mechanical/Destructive testing setup

Mechanical testing of laminated specimens has been done to evaluate the ultimate strength in tension & bending, before & after the exposure to hygro-thermal loading in order to determine the actual decrease in strength after different time durations (15 & 30 days). Also tensile loading of specimens has been done at different percentage of ultimate tensile load in order to evaluate damage caused by mechanical loading with help of ultrasonic testing.

4.4.3.1 Tensile testing machine

(a) **(b)**

Fig. 4.32 (a) Tensile testing machine (b) Gripped specimen

A Universal Tensile testing machine shown in Fig.4.32 has been used for the testing of the FRP specimen for its tensile strength. Maximum Capacity of UTM is 1000 kN. The test specimens have been prepared according to ASTM-D-3790 standard as mentioned in article 4.2. This machine has been used for subjecting the specimens at different levels of mechanical loading. Also this machine has been used to evaluate tensile strength of specimen subjected to Hygro-thermal loading for different duration of time period to estimate the degradation.

4.4.3.2 Three point bending machine

Three point bending testing shown in Fig.4.33 has been used for the testing of the FRP specimen for its flexural strength. Maximum Capacity of machine is 10 kN.

(a) **(b)**

Fig. 4.33 (a) 3-point bending machine (b) loaded specimen

This machine can also perform tensile loading but the maximum loading capacity of this machine is low as compared to ultimate load of laminate specimens in tensile loading. For this reason UTM as discussed above has been used to determine the tensile strength & this machine has been used to carry out flexural strength determination of specimens subjected to Hygro-thermal loading.

4.5 Test Matrices

Matrices of number of specimen for different type of testing are shown here. One test matrix is made for Hygro-thermal loading, second is for mechanical loading and third one is made for simulated delamination study for the GFRP composite laminates.

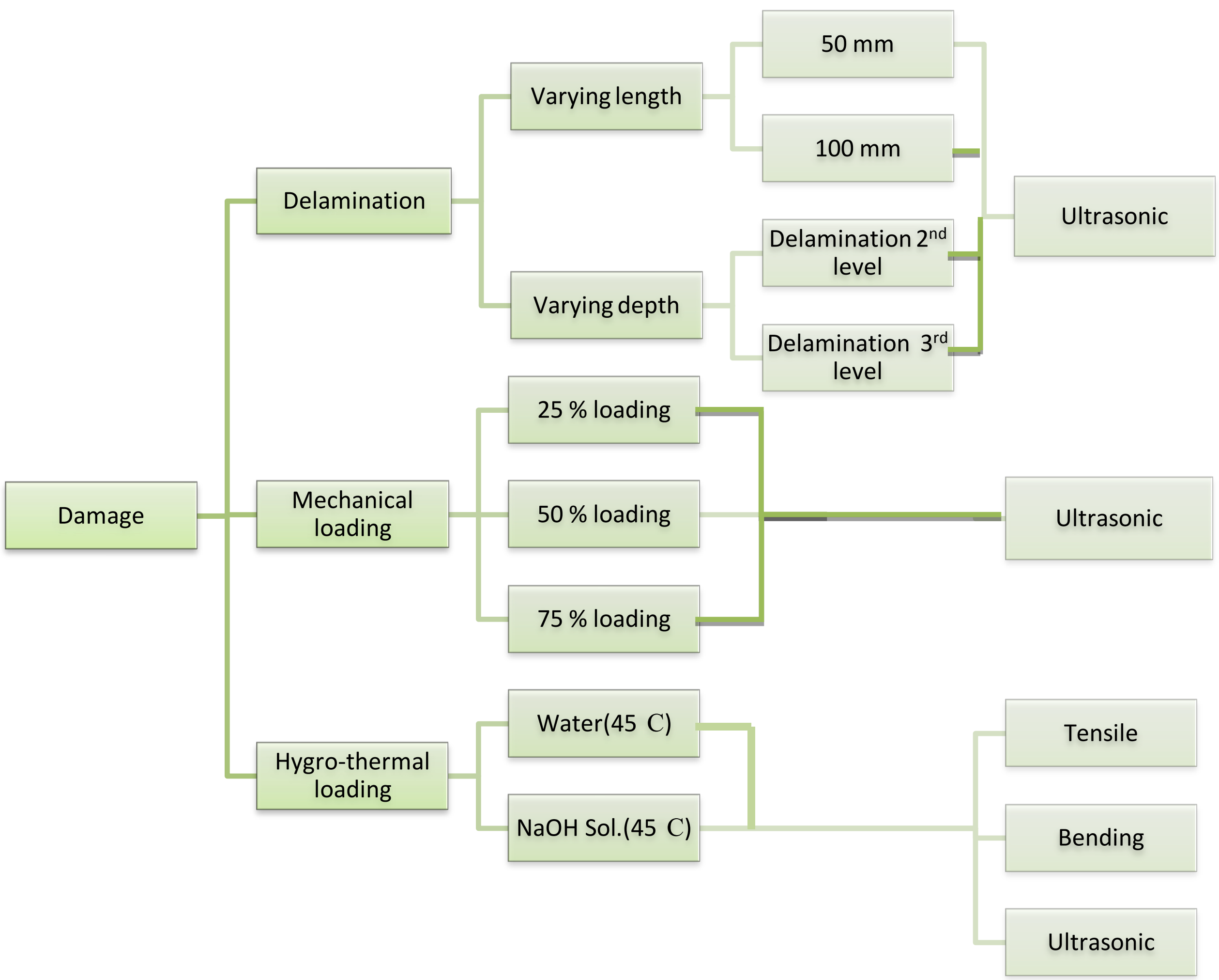


Fig. 4.34 Work plan

Table T4.3: Test matrix for Hygro-thermal loading

Bath type	Testing Type	Holding Time			Total Specimen
		0 day(Initial)	15 days	30 days	
Water bath (45°C)	Tensile	2	2	2	6
	Bending	2	2	2	6
	Ultrasonic	2	2	2	6
NaOH bath (45°C)	Tensile	2	2	2	6
	Bending	2	2	2	6
	Ultrasonic	2	2	2	6
Total specimen					36

Table 4.4: Test matrix for Mechanical loading at different percentage of ultimate load

Specimen Type	Type of loading		Total Specimen
	Tensile	Bending	
Specimen for ultimate load	2	2	4
Specimen at 25% of ultimate load	2	2	4
Specimen at 50% of ultimate load	2	2	4
Specimen at 75% of ultimate load	2	2	4
Total Specimen			16

Table 4.5: Test matrix for Simulated Delamination study

Delamination(Varying length)	
Specimen type	**No. of Specimen**
Delamination 50 length	2
Delamination 100 length	2
Delamination(Varying Depth)	
Delamination 2nd Level	2
Delamination 3rd Level	2
Total Specimen	8

Closure

This chapter had discussed size & specifications of specimens required for different experiment work & detailed procedural steps required to fabricate the GFRP composite laminate specimens**.** Also experimental setups & mechanical testing machine required to carry out the planned work has been discussed. In the last test matrices has been given for specifying the number of samples required for each study.

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

CHAPTER 5 RESULTS AND DISCUSSIONS

5.1 Introduction

Experimentation has been conducted on the laminate specimens according to test matrix. Various graphs obtained from tensile testing, flexural testing & ultrasonic testing before & after degradation has been shown here. Table of results has been formulated & comparison of different samples after seeded/exposed damage with that of healthy/reference specimens in terms of percentage decrease in strength have been discussed. Ultrasonic through transmission testing has been done on specimen to obtain reference/benchmark signature. Different angle setting & probe-probe distance has been tested to obtain the particular angle which generates the lamb mode most suitable to detect damage.

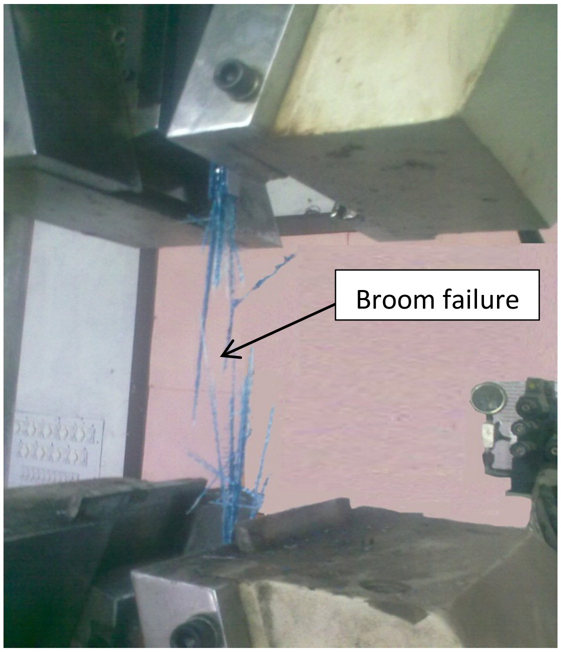
5.2 Hygro-thermal damage evaluation

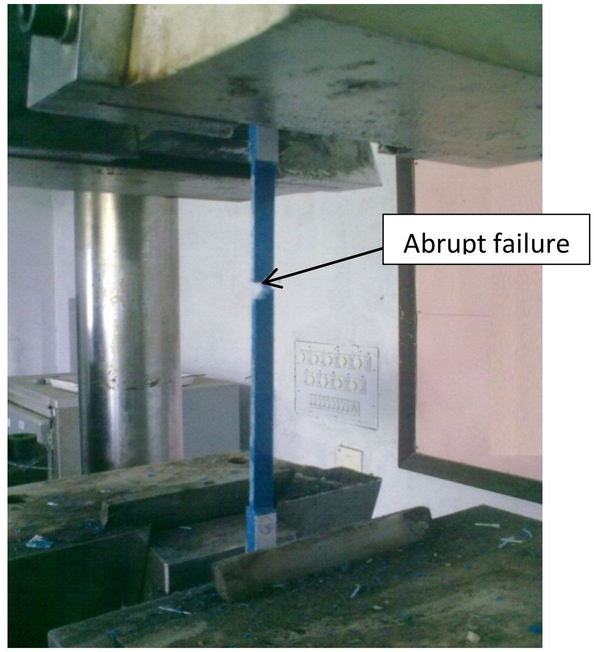
Hygro-thermal loading consists of subjecting specimens to extreme conditions (NaOH & water at 45°C temperature) for different durations of time which leads to degradation of specimens.An attempt has been made to study the variation in tensile strength, flexural strength & changes in these properties have been co-related with corresponding change in ultrasonic signature. Ultrasonic signature of detoriated specimens have been compared with of healthy specimens to evaluate decrease in properties, which helps in doing structural health monitoring of composite structures.

5.2.1 Visual Observations

As per the visual observation the initial healthy specimens had fine shiny epoxy coating whereas degraded specimen after hygro-thermal loading shown dull surface. Specimens subjected to NaOH environment shows scale formation on the surface as shown in fig. 5.2(c).

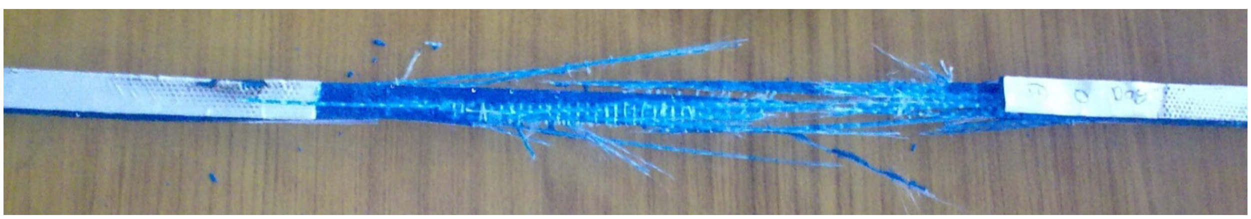
From mechanical testing of specimens it has been observed that the failure of healthy specimen under uni-axial tensile load showed a broom type failure as shown in fig 5.1(a). This may be due to sudden and violent release of stored elastic energy. On the other hand fig. 5.1(b) showed the failure of degraded specimen exposed to 30 days of hygro-thermal loading which was abrupt failure because of loss in flexibility & strength.





(a) **(b)**

Fig. 5.1 Failure of specimen on machine (a) healthy specimen (b) specimen after degradation



(a)

(b)

(c)

Fig. 5.2 Failure mode (a) Broom failure (b) Abrupt failure (c) Shear failure

5.2.2 Experimental data of Healthy Specimens (Reference specimens)

First tensile strength, flexural strength & ultrasonic signature of healthy specimens for hygro-thermal study have been taken to obtain benchmark/reference data against which the experimental data of Hygro-thermally loaded specimens for different duration of time is compared. This comparison has helped in evaluating the damage.

a) **Tensile test graph:** Initially healthy specimens have been tested on UTM to obtain the ultimate tensile strength, yield strength, young's modulus of elasticity, elongation etc. Graph below shows the stress-strain graph.

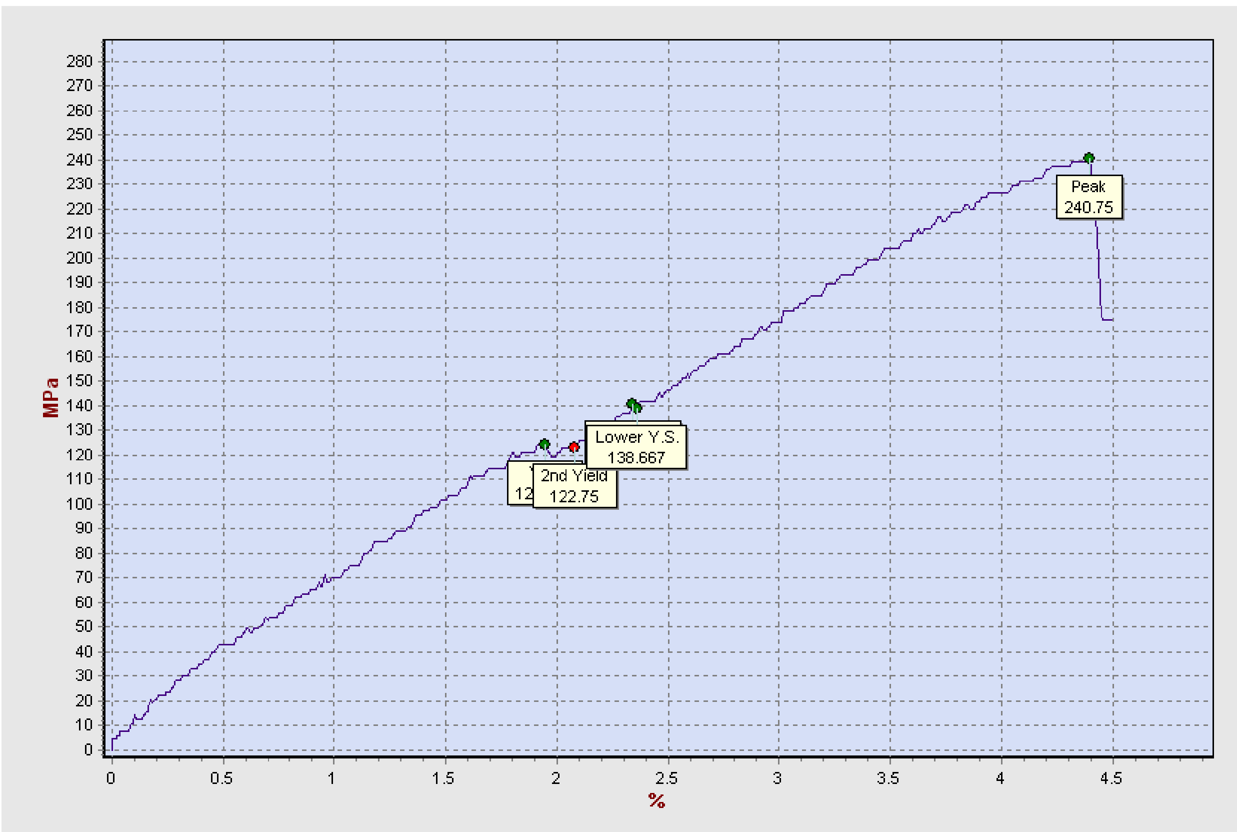


Fig. 5.3 Stress-strain graph for Healthy specimen in tensile loading

b) **Flexural test graph:** Experimental data related with bending of healthy laminated specimen has been calculated on 3-point bending machine. Corresponding graph has been shown below.

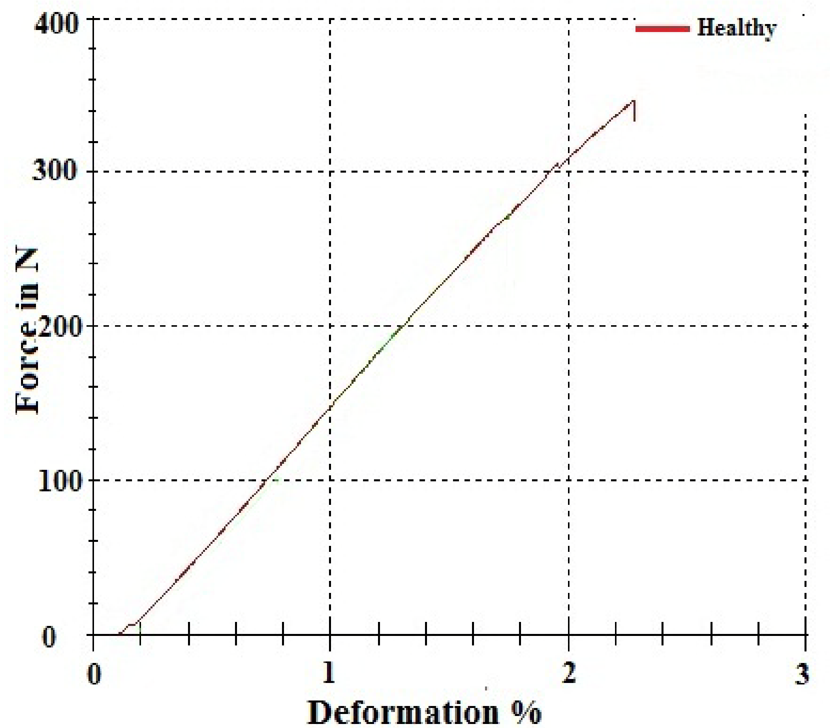


Fig. 5.4 Load-deformation graph for healthy specimen in flexural loading

c) **Ultrasonic testing signature:** Ultrasonic through transmission testing has been done on specimen to obtain reference/benchmark signature. Transducer of 0.5 MHz frequency at angle of 18° has been used because this setting gives most observable change in amplitude.

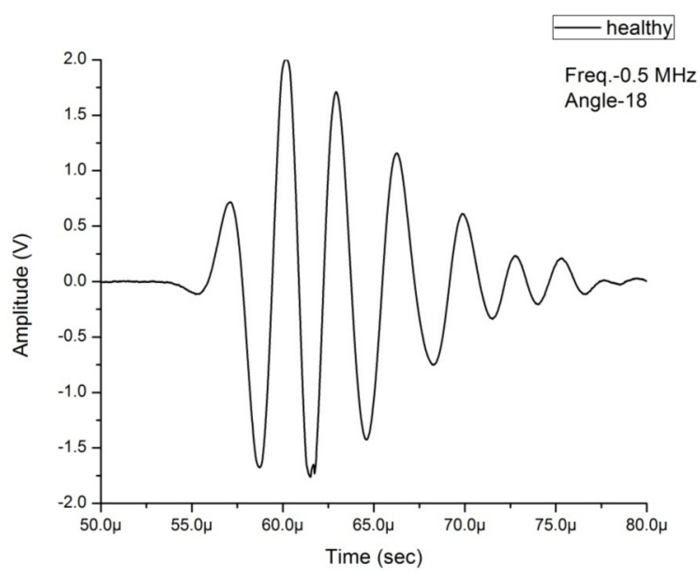


Fig. 5.5 Through Transmission signature of healthy specimen in ultrasonic testing

5.2.3 Experimental data for degraded specimens exposed to hygro-thermal loading for 15 Days

According to test matrix specimens subjected to Hygro-thermal exposure have been taken out after 15 days & further destructive & nor-destructive testing has been done to obtain the experimental data. Various graphs obtained for respective testing has been shown below.

1. Tensile test graph

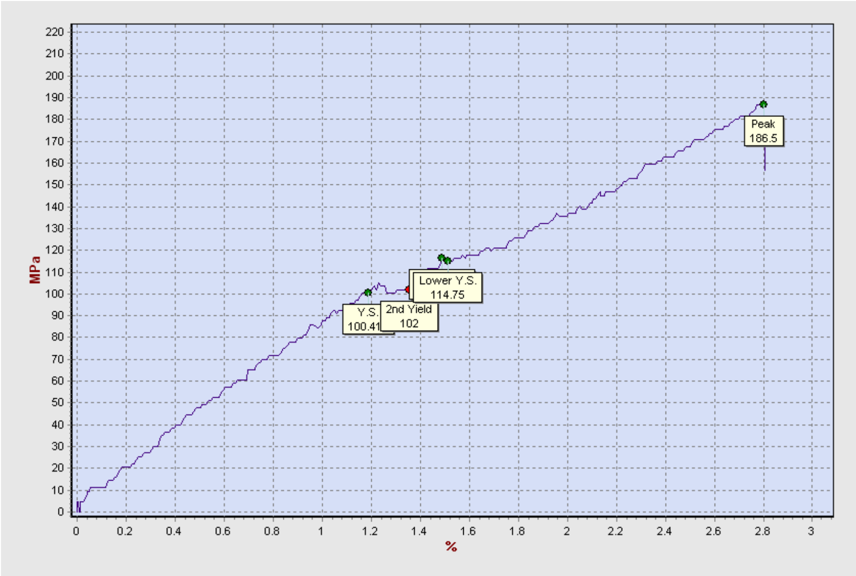


Fig. 5.6 Stress-strain graph for specimen exposed to hygro-thermal loading in water tank for 15 days

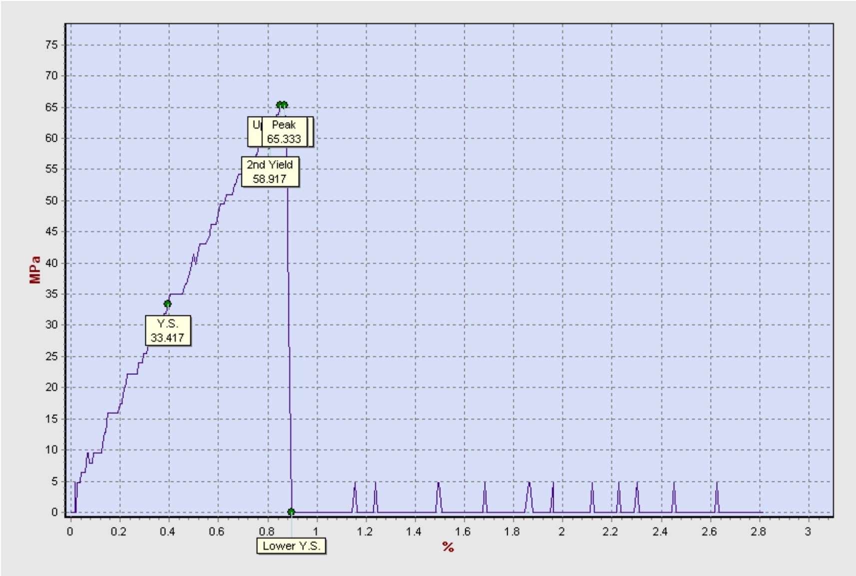
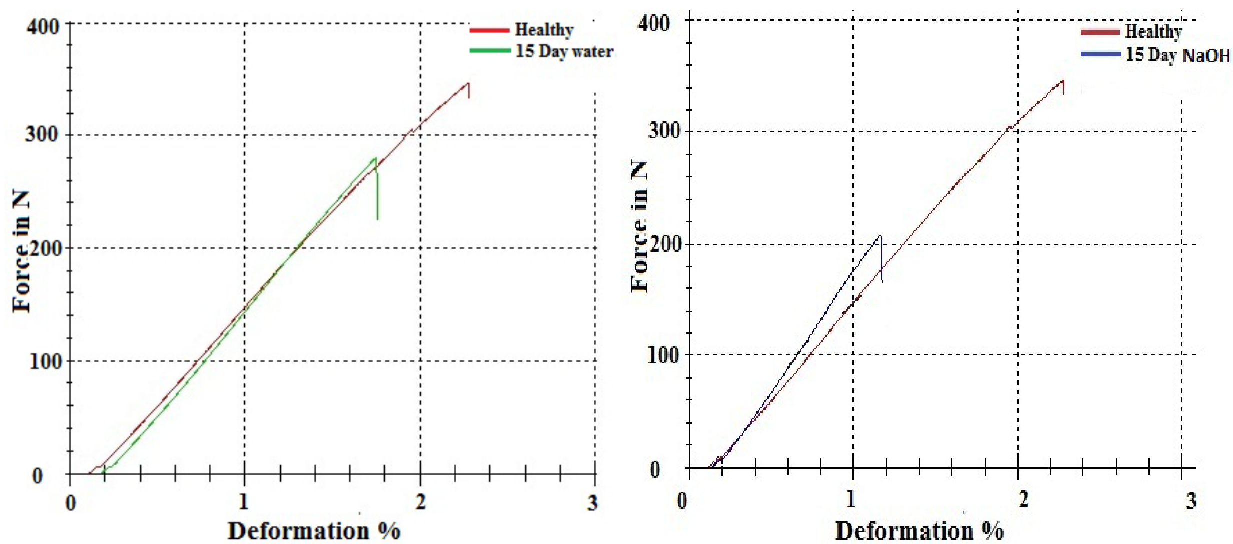


Fig. 5.7 Stress-strain graph for specimens exposed to hygro-thermal loading in NaOH tank for 15 days

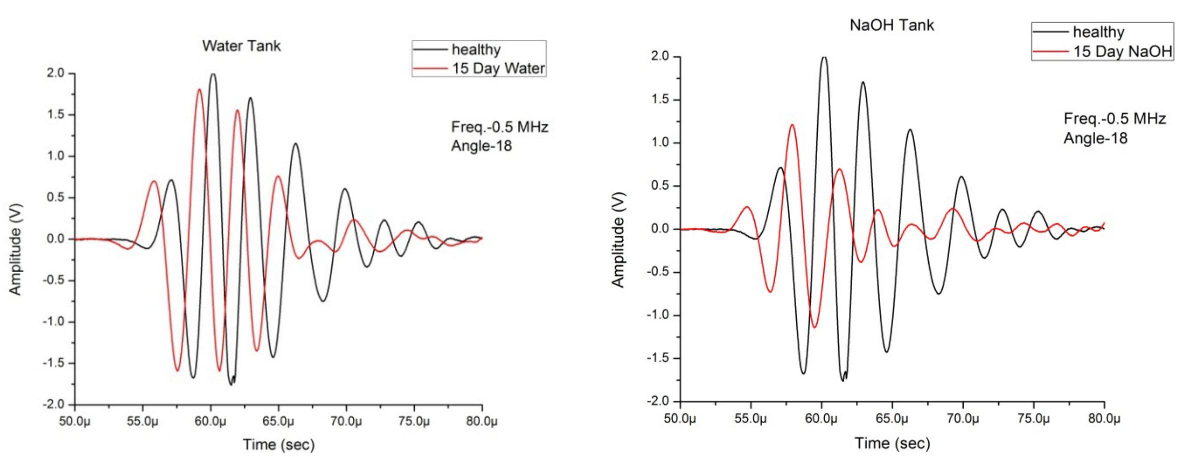
2. Flexural test graph



(a) (b)

Fig. 5.8 Load-deformation graph for specimens exposed to hygro-thermal loading for 15 days in (a) water tank (b) NaOH tank

3. Ultrasonic testing signature



(a) (b)

Fig. 5.9 Through Transmission signature for specimens exposed to hygro-thermal loading for 15 days in (a) Water tank (b) NaOH tank

Discussion

1. It has been observed from above graphs that there was decrease in tensile strength of laminated specimens after 15 days of exposure to hygro-thermal loading conditions when compared to healthy specimen results. But the specimens exposed to NaOH environment had shown greater reduction in tensile strength as compared to water environment.
2. Similar trend has been seen in flexural testing of laminated specimen. Both NaOH & water tank specimens had shown reduction in ultimate flexural load taken before failure after 15 days exposure to hygro-thermal loading. In case of NaOH tank specimens, reduction in flexural strength has been much greater than water tank specimens.
3. In the case of ultrasonic testing, through transmission signature obtained after testing the specimens subjected to hygro-thermal loading for 15 days showed reduction in peak to peak amplitude as compared to signature of healthy specimens.

The reason for decrease in ultimate tensile strength, flexural strength and ultrasonic signal amplitude seems to be the continuous degradation done by hygro-thermal load which affected the epoxy and fibre strength.

5.2.4 Experimental data for degraded specimens exposed to hygro-thermal loading for 30 Days

As specified in test matrix, specimens subjected to Hygro-thermal exposure have been taken out after 30 days & further destructive & nor-destructive testing has been done to obtain the experimental data. Various graphs obtained for respective testing has been shown in fig 5.10-5.13

1. **Tensile test graph**

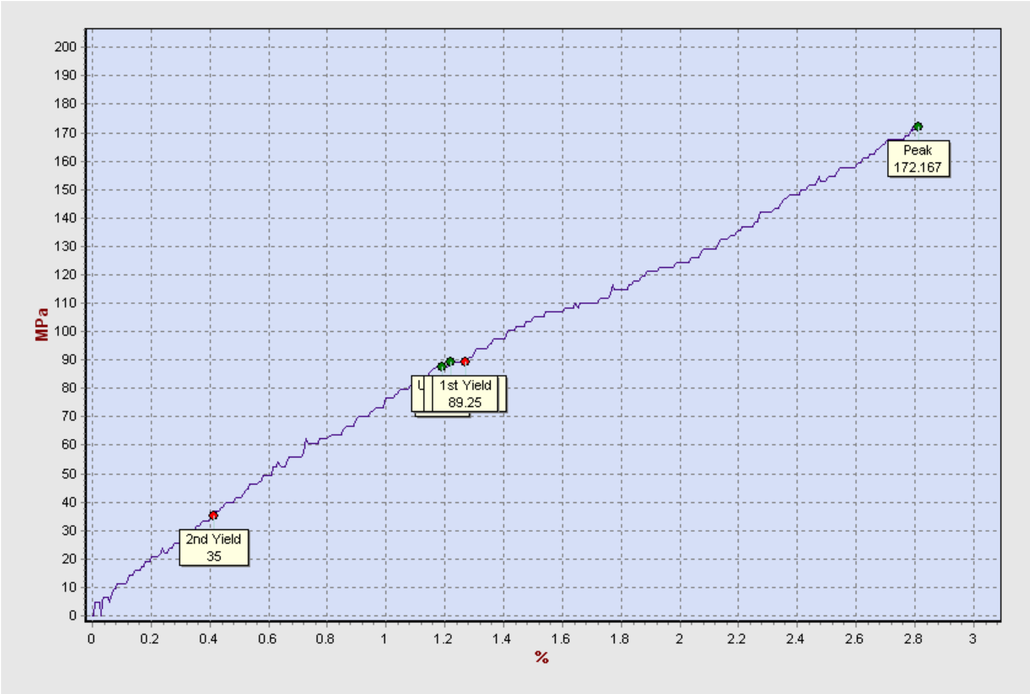


Fig. 5.10 Stress-strain graph for specimen exposed to hygro-thermal loading in water tank for 30 days

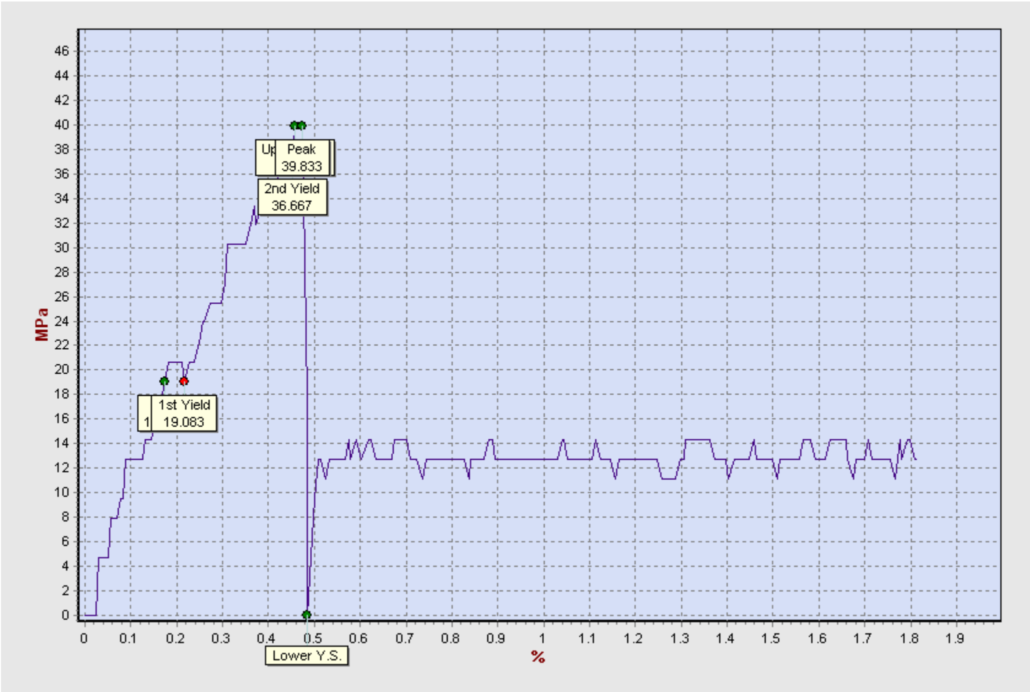
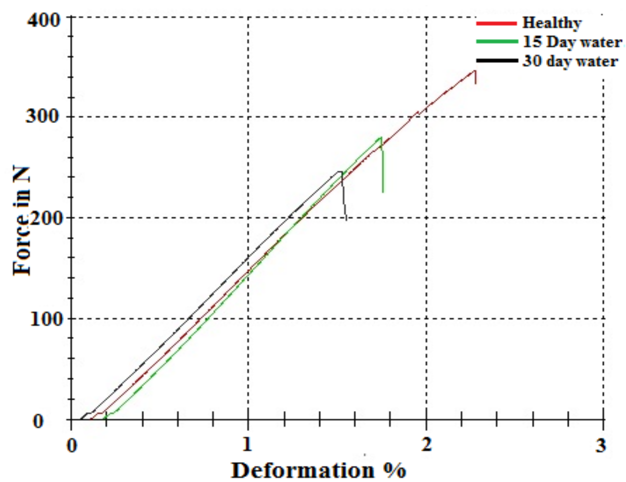
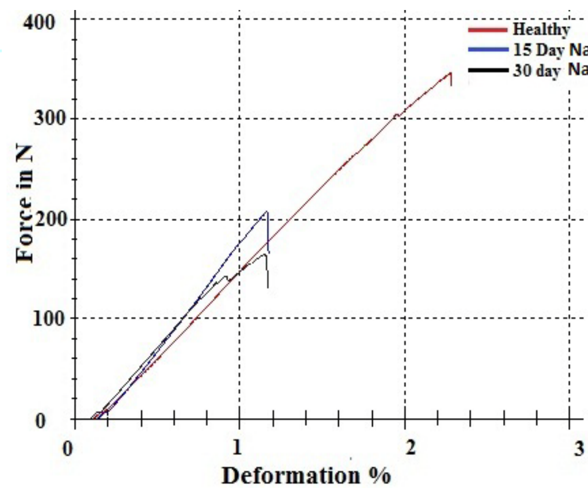


Fig. 5.11 Stress-strain graph for specimens exposed to hygro-thermal loading in NaOH tank for 30 days

2. Flexural test graph

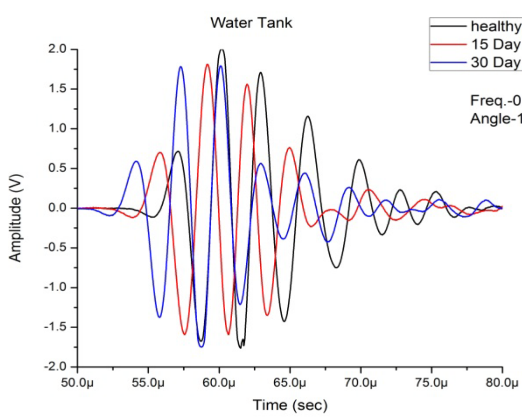


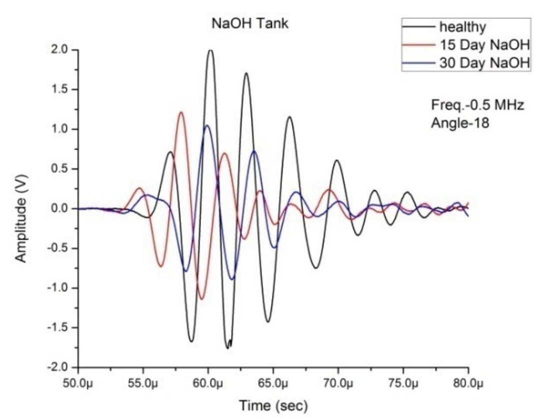


(a) (b)

Fig. 5.12 Load-deformation graph for specimens exposed to hygro-thermal loading for 30 days in (a) water tank (b) NaOH tank

3. Ultrasonic testing signature





(a) (b)

Fig. 5.13 Through Transmission signature for specimens exposed to hygro-thermal loading for 30 days in (a) water tank (b) NaOH tank

Discussion

1. It has been observed from above graphs that decrease in tensile strength of laminated specimens after 30 days of exposure to hygro-thermal loading conditions not that much prominent when compared to drop in first 15 days for both NaOH & water tank specimens.

2. Similar trend has been seen in flexural testing of laminated specimen. Both NaOH & water tank specimens had shown reduction in ultimate flexural load taken before failure but rate of decrease is less after 30 days as compared to first 15 days.
3. For ultrasonic testing, through transmission signature obtained after testing the specimens subjected to hygro-thermal loading showed reduction in peak to peak amplitude after 30 days exposure to hygro-thermal load as compared to signature of healthy specimens & specimens agter 15 days of exposure.

5.2.5 Experimental results obtained from specimens subjected to hygro-thermal loading for different time durations

Table 5.1 Percentage decrease in Tensile strength of laminates for Water tank

Water tank (45°C Temp)						
No. of days	**Sample no.**	**Peak Load (N)**	**Tensile Strength (Mpa)**	**Yield Strength (Mpa)**	**Young Modulus**	**% Decrease in Strength**
0 day	sample 1	14445	240.75	124.33	4844.23	**0**
	sample 2	12340	205.67	105.17	4254.26	
15 day	sample 1	11190	186.50	100.42	4369.34	**19.66**
	sample 2	10330	172.17	116.33	5841.84	
30 day	sample 1	10335	172.20	87.67	4537.78	**30.72**
	sample 2	8225	137.08	113.17	5350.57	

Table 5.2 Percentage decrease in Tensile strength of laminates for NaOH tank

Noah tank (45°C Temp)						
No. of days	**Sample no.**	**Peak Load (N)**	**Tensile Strength (Mpa)**	**Yield Strength (Mpa)**	**Young Modulus**	**% Decrease in Strength**
0 day	sample 1	14445	240.75	124.33	4844.23	**0**
	sample 2	12340	205.67	105.17	4254.26	
15 day	sample 1	3920	65.33	33.42	7071.06	**71.09**
	sample 2	3825	63.75	28.67	6864.88	
30 day	sample 1	2390	39.83	19.08	5756.94	**84.66**
	sample 2	1720	28.67	25.50	8943.52	

Table 5.3 Percentage decrease in Flexural strength of laminates for Water tank

Water tank (45°C Temp)				
No. of days	**Sample no.**	**Peak Load (N)**	**Flexural Strength(MPa)**	**% Decrease in Strength**
0 day	sample 1	347.25	400.13	**0**
	sample 2	282.13	325.24	
15 day	sample 1	287.45	331.12	**9.68**
	sample 2	281.62	324.03	
30 day	sample 1	246.14	284.11	**14.63**
	sample 2	290.92	335.14	

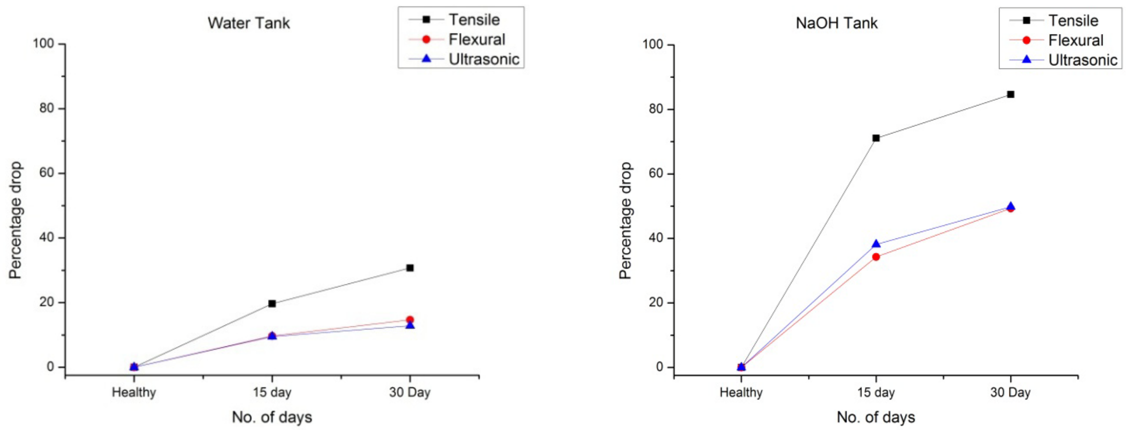
Table 5.4 Percentage decrease in Flexural strength of laminates for NaOH tank

Noah tank (45°C Temp)				
No. of days	**Sample no.**	**Peak Load (N)**	**Flexural Strength(MPa)**	**% Decrease in Strength**
0 day	sample 1	347.32	400.56	**0**
	sample 2	282.27	325.13	
15 day	sample 1	208.19	240.43	**34.26**
	sample 2	205.21	236.65	
30 day	sample 1	164.28	189.20	**49.34**
	sample 2	154.23	178.42	

Table 5.5 Percentage decrease in through transmission signal amplitude of laminates for NaOH & Water tank

No. of days	**Sample no.**	**Water Tank**		**Noah Tank**	
		Pk-Pk Amplitude (V)	**% Decrease in Amplitude**	**Pk-Pk Amplitude (V)**	**% Decrease in Amplitude**
0 day	sample 1	3.76	**0.00**	3.76	**0.00**
	sample 2	3.71		3.71	
15 day	sample 1	3.40	**9.50**	2.34	**38.15**
	sample 2	3.36		2.28	
30 day	sample 1	3.40	**12.85**	1.94	**49.80**
	sample 2	3.11		1.81	

5.2.6 Comparison of Tensile strength, flexural strength & ultrasonic signal in terms of percentage drop



(a) **(b)**

Fig. 5.14 Comparison of percentage drop for (a) water tank (b) NaOH tank

Discussions on hygro-thermal results

The above graphs showed comparison of tensile strength, flexural strength & through transmission signal amplitude decrease in terms of percentage drop over healthy specimens when subjected to hygro-thermal loading for different duration of time.

- In water tank, comparison showed that there is 20% decrease in tensile strength after 15 days which increased to 31% after 30 days of exposure to hygro-thermal conditions. Similarly flexural strength showed reduction in 10% & 15% after exposing the laminate specimens to 15 & 30 days. Similar trend has been shown by ultrasonic testing of exposed laminate specimens. There was drop of 10 % in amplitude after 15 days of exposure which increased to 13 % after 30 days.
- NaOH tank specimens had shown greater decrease in properties as compared to water tank for same exposure period. Tensile strength reduction has been substantial to 70 % after 15 days which has further increased to 86% after 30 days. Similar trend has been seen in flexural strength which reduces to 50% after 30 days of exposure. Through transmission signal amplitude had shown similar reduction as was for flexural strength. Percentage loss in amplitude after 15 days was 38% which had increased to 50% after 30 days exposure to hygro-thermal loading.

The reason for decrease in ultimate tensile strength and flexural strength seems to be the continuous degradation done by hygro-thermal load which affected the epoxy and fibre strength. Further in NaOH tanks the reason for such large reduction is that epoxy has been subjected to chemical attack as well which had made it brittle. Also there is decrease in through transmission signal amplitude which is due to loss of adhesion or de-bonding at the fiber–matrix interface, moisture absorption, matrix swelling, and chemical attack on matrix as well as fibre which results in more dispersion of signal.

5.3 Mechanical Damage Evaluation

In this experiment the damages (stresses) produced in the composite plates while under actual working conditions has been simulated by loading specimen at different percentage of ultimate tensile load & then evaluated the damage caused with the help of ultrasonic signal drop. As with the passage of time these stresses increases which leads to ultimate failure of component. So to depict those phenomena, different laminated specimens had been loaded with some percentage (25%, 50% & 75%) of ultimate tensile load which caused the formation of damage in terms of fibre stretching, matrix cracking, fibre pull-out etc. & then relate this damage in terms of through transmission signal drop. This leads to health monitoring of composite specimens with ultrasonic testing.

Ultrasonic testing has been done with 0.5 & 1 MHz immersion transducer at different angle setting. Finally optimized angle of 23° has been used for evaluation of damage caused by mechanical loading.

5.3.1 Tensile testing of Specimens to determine ultimate load

The tensile test of healthy sample was first conducted on a Universal Testing Machine to determine the actual ultimate load (peak load) the sample can bear. On basis of that ultimate load the loading weight for samples was calculated which then loaded with 25%, 50% & 75% of ultimate load. The specifications of specimens used for mechanical loading had been discussed in chapter 4. The graph for ultimate load determination has been shown in fig 5.15

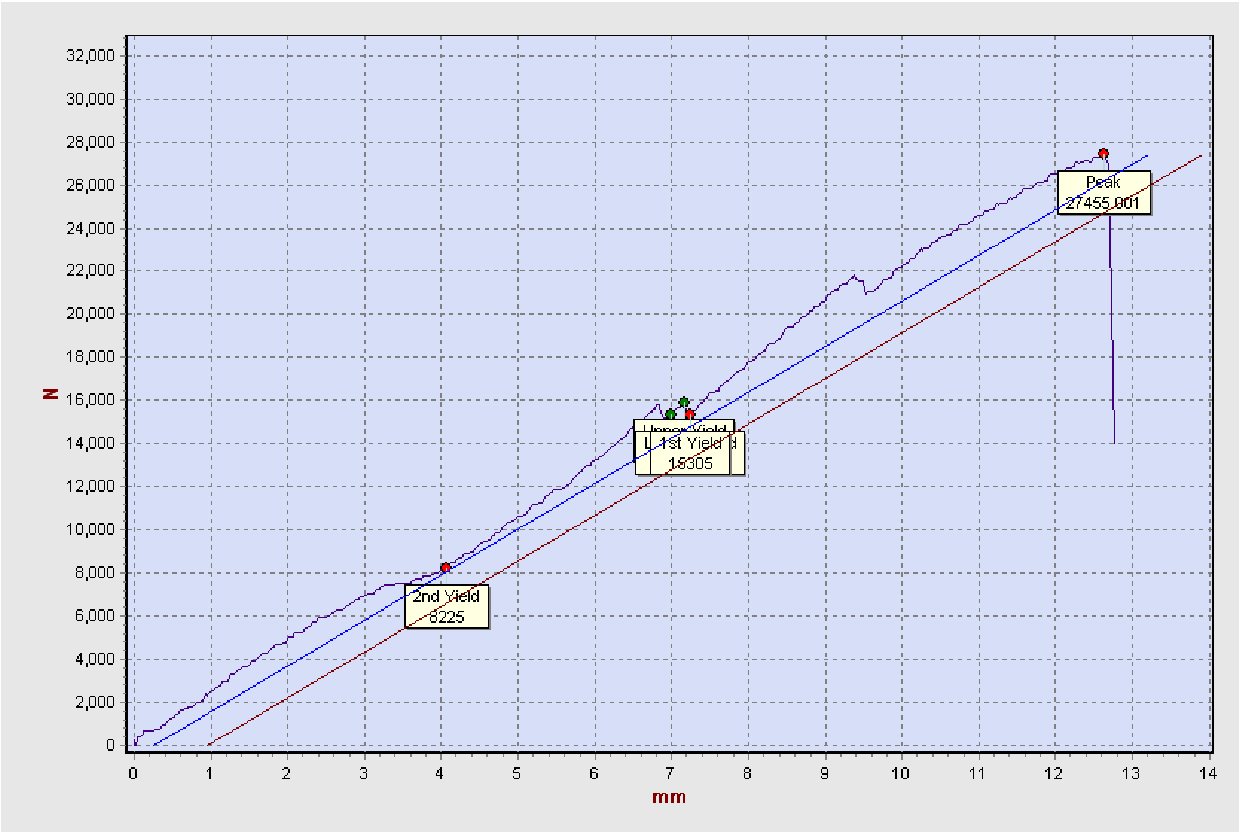


Fig. 5.15 Load-deformation graph for healthy (reference) specimen to determine ultimate load

5.3.2 Loading value of specimens at percentage of Ultimate tensile load

Following table shows values at which the specimens were subjected to different percentage of ultimate load.

Table 5.6 Loading of laminated specimen at percentage of ultimate load

Tensile Loading			
Sample no.	**Peak Load (N)**	**Tensile Strength(MPa)**	**Yield Strength(MPa)**
Healthy	27455	171.59	95.66
25% loading	6695 *	41.84	38.84
50% loading	13870 *	86.69	68.16
75% loading	22100 *	138.13	123.16

* Actual values are the loading value shown by tensile testing machine.

5.3.3 Results of testing on specimens subjected to 25% of ultimate tensile loading

The maximum load on machine for tensile stretching has been set to 25% of ultimate load. Here it has been set to 6700 N .This is somewhat lower than exact 25% loading because UTM has some defined incremental load steps.

A) Tensile testing graph

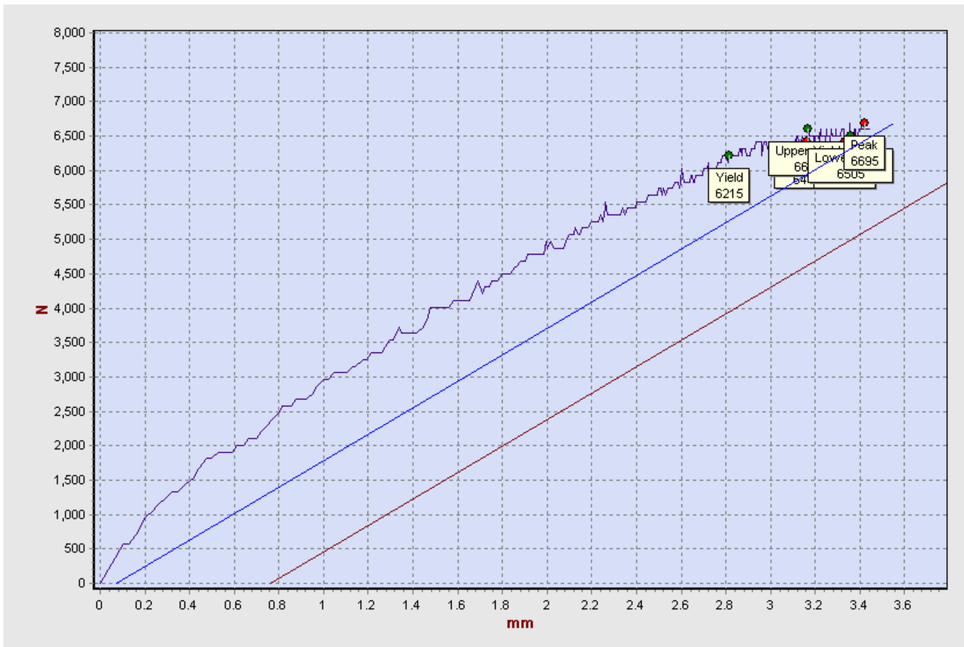
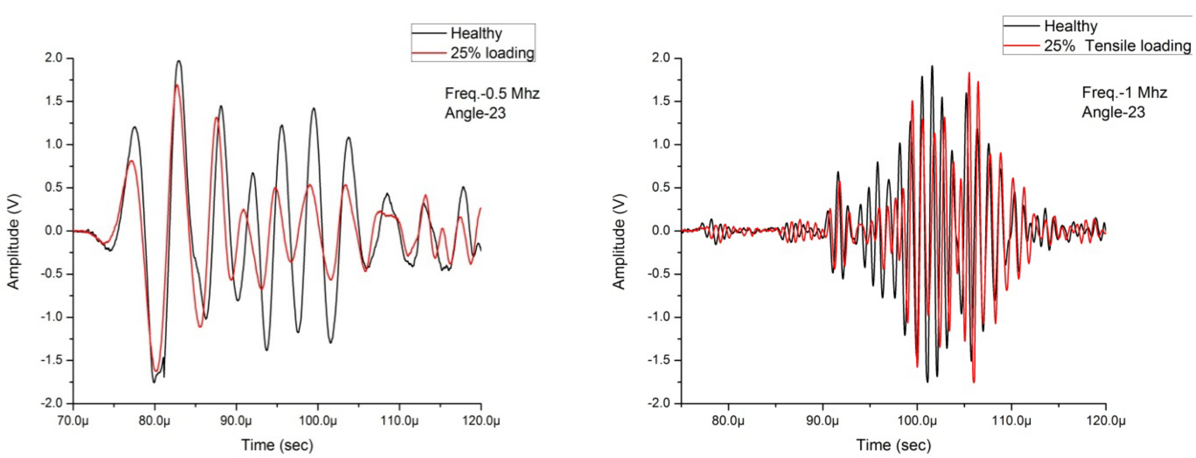


Fig. 5.16 Load-deformation graph for specimens subjected to 25% of ultimate tensile loading

B) Ultrasonic testing signature



(a) **(b)**

Fig. 5.17 Through transmission signature of specimens subjected to 25% of ultimate tensile loading at (a) 0.5 MHz (b) 1 MHz

5.3.4 Results of testing on specimens subjected to 50% of ultimate tensile loading

The maximum load on machine for tensile stretching has been set to 50% of ultimate load. Here it has been set to 13800 N.

A) Tensile testing graph

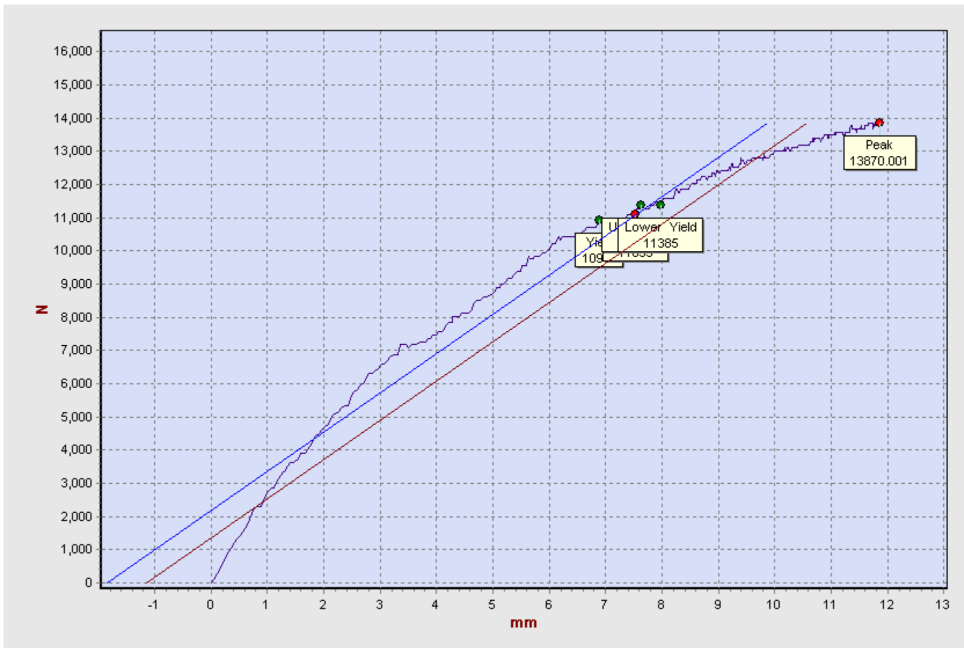
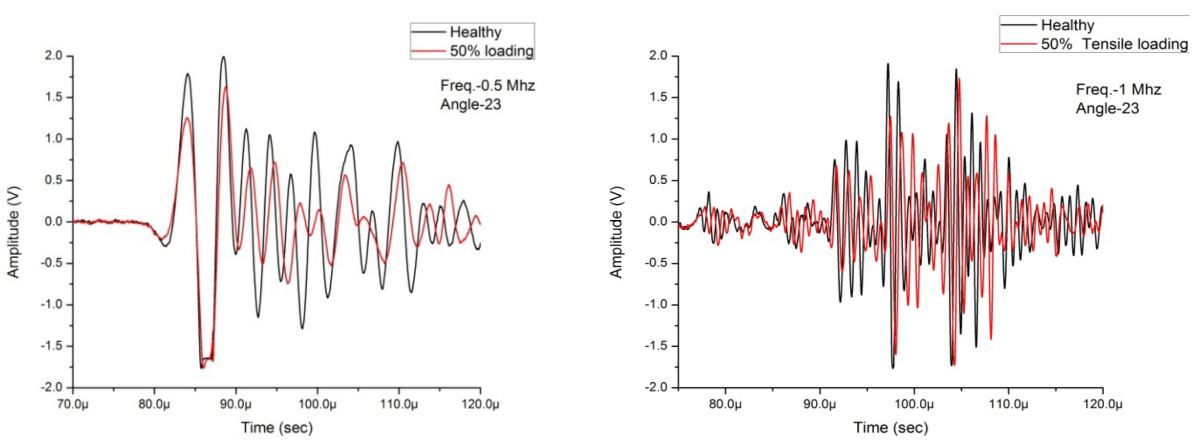


Fig. 5.18 Load-deformation graph for specimens subjected to 50% of ultimate tensile loading

B) Ultrasonic testing signature



(a) **(b)**

Fig. 5.19 Through transmission signature of specimens subjected to 50% of ultimate tensile loading at (a) 0.5 MHz (b) 1 MHz

5.3.5 Results of testing on specimens subjected to 75% of ultimate tensile loading

The maximum load on machine for tensile stretching has been set to 75% of ultimate load. Here it has been set to 22000 N.

A) Tensile testing graph

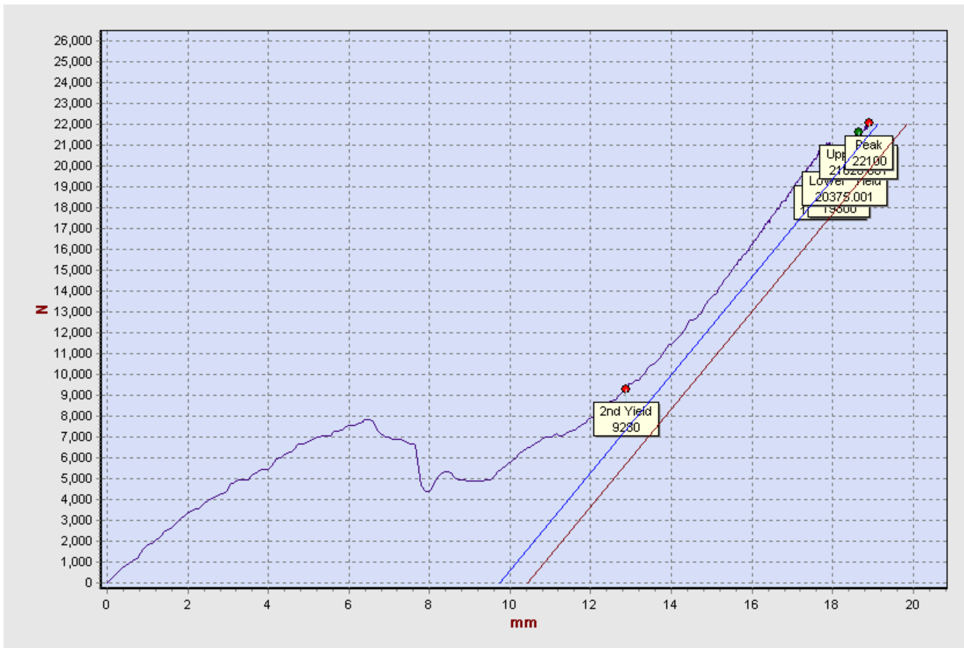
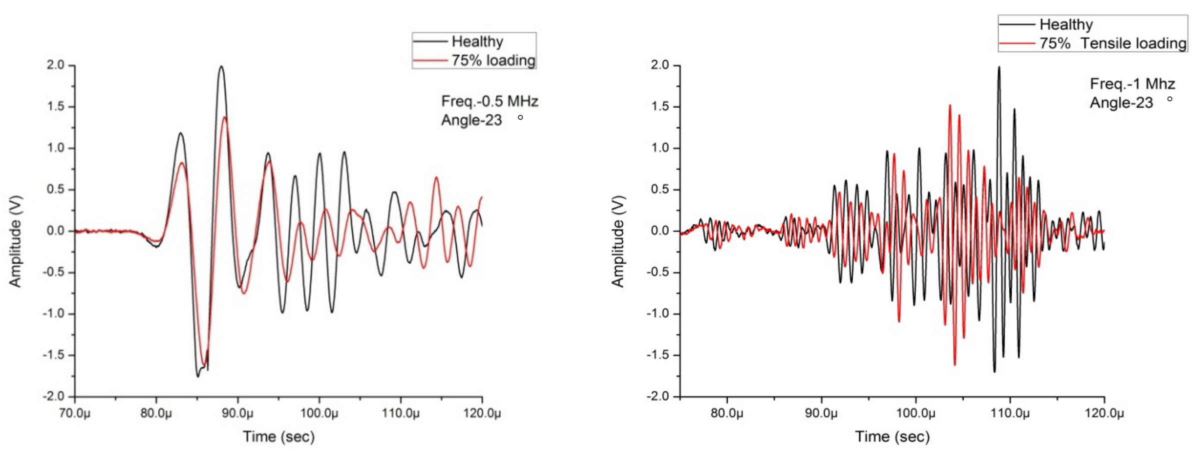


Fig. 5.20 Load-deformation graph for specimens subjected to 75% of ultimate tensile loading

B) Ultrasonic testing signature



(a) **(b)**

Fig. 5.21 Through transmission signature of specimens subjected to 75% of ultimate tensile loading at (a) 0.5 MHz (b) 1 MHz

5.3.6 Ultrasonic through transmission signature results of specimen subjected to tensile loading

Table 5.7 Percentage decrease in through transmission signal amplitude of laminates

Sample name	Freq.-0.5 Mhz (Pk-Pk Amplitude (V))		%Decrease in Amplitude	Freq.-1 Mhz (Pk-Pk Amplitude (V))		%Decrease in Amplitude
	Healthy	Stretched		Healthy	Stretched	
25 % loading	3.72	3.31	**11.02**	3.74	3.59	**4.01**
50 % loading	3.76	3.26	**13.30**	3.68	3.44	**6.52**
75 % loading	3.75	2.99	**20.27**	3.69	3.14	**14.91**

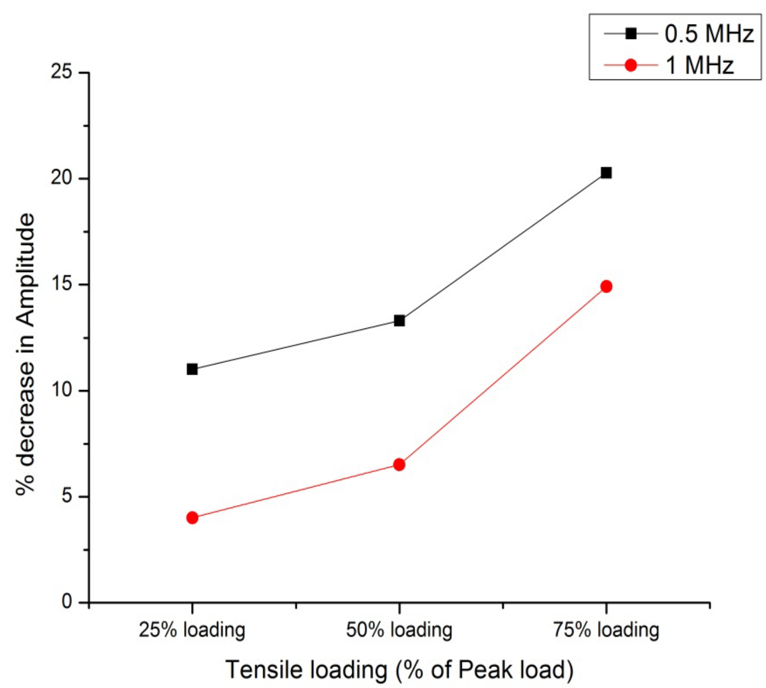


Fig. 5.22 Comparison of decrease in signal strength with loading

Discussions on Mechanical loading evaluation

It was observed from above results that with the increase in loading of specimen there has been drop in through transmission signal amplitude. As due to loading of laminates at different percentage, stretching had taken place which creates matrix cracking, voids, fibre-pullout etc. which affects the through transmission signature by attenuation, damping, scattering etc.

Specimen loaded with 25% of peak load had shown some decrease in signal amplitude about 11 % but when loading increased to 50% there was only marginal decrease in signal amplitude as compared to 25 % loaded specimen. This may be due to elastic nature of fibre which regained some of its strength when loading was removed. As loading was within elastic stage, so not much effect had taken place on signal amplitude. But specimen loaded with 75% of peak load crossed the elastic limit stage & cause the fibre pull-out, breakage, matrix-cracks which considerably affect the signal amplitude (about 20 %).

Specimens have been tested at both 0.5 MHz & 1MHz frequencies but 0.5 MHz frequency testing had shown better results.

5.4 Simulated delamination defect evaluation

Delamination defect is one of the major cause of failure in composite laminated structures. Delamination is de-bonding in between the adjustened layers due to application of load or environmental degradation. So in order to identify & evaluate the delamination, experimental study about delamination has been done. Two type of delamination has been simulated, one delamination by varying the extent (length) & second by introducing the delamination at different depth (in between different layers) with the help of ultrasonic testing setup. Through transmission signatures have been mapped to determine the extent of delamination & pulse-eco signatures have been used to determine location & size of delamination.

5.4.1. Delamination of varying extent (length)

In this study, delaminations of varying extent were provided in between the layer of composite laminated specimen. Basic aim of this study is to map ultrasonic lamb wave signatures of specimens with seeded delamination defect of varying extend & studying the drop in signal amplitude with increase in delamination extent.

Delamination extent has been evaluated on specimen having different length delamination in two layers laminate. The size & specification of specimen used for delamination study has been discussed in chapter 4. Transducer of 0.5 MHz frequency has been used at various angle settings to identify which angle is best suitable to excite particular mode that can detect delamination & its extent. After careful examination of through transmission signature at various angles, 23° has been found to be best suitable to find delamination in between layers of laminate.

5.4.1.1 Evaluation of extent of delamination defect using through transmission signatures

Through transmission signature over healthy region has been taken & then compared with the signature taken over delamination region of different length with same angle setting & probe-probe distance.

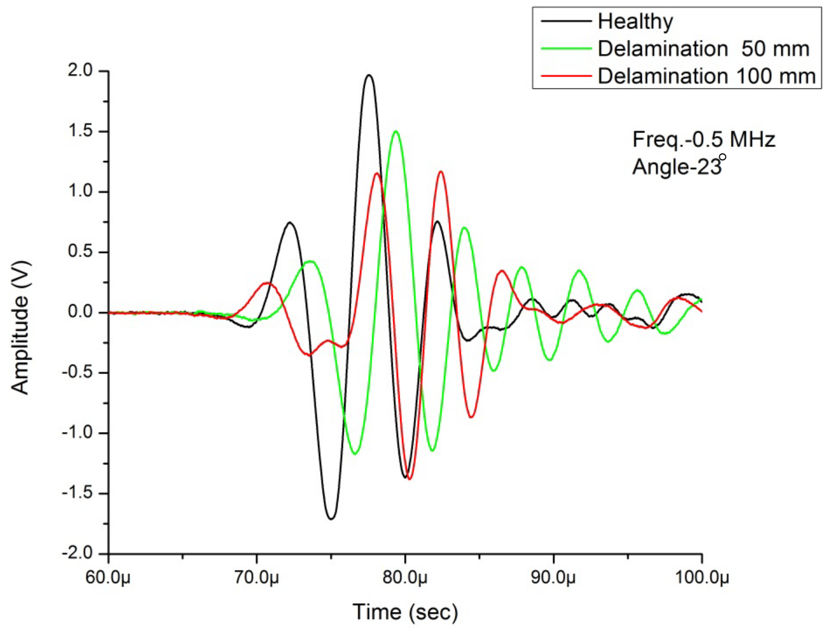


Fig. 5.23 Through transmission signature of specimens having varying delamination extent

5.4.1.2 Results of through transmission signatures for delamination of varying extent

Table 5.8 Through transmission amplitude for various Delamination extent

S.No.	Delamination length(mm)	Pk-Pk Amplitude (V)	% Decrease in amplitude
1	Healthy	3.68	**0**
2	Delamination (50)	2.67	**27.45**
3	Delamination (100)	2.24	**39.13**

5.4.1.3 Percentage drop in through transmission signatures for delamination of varying extent

The percentage drop through signal amplitude at different delamination extent has been shown in graph.

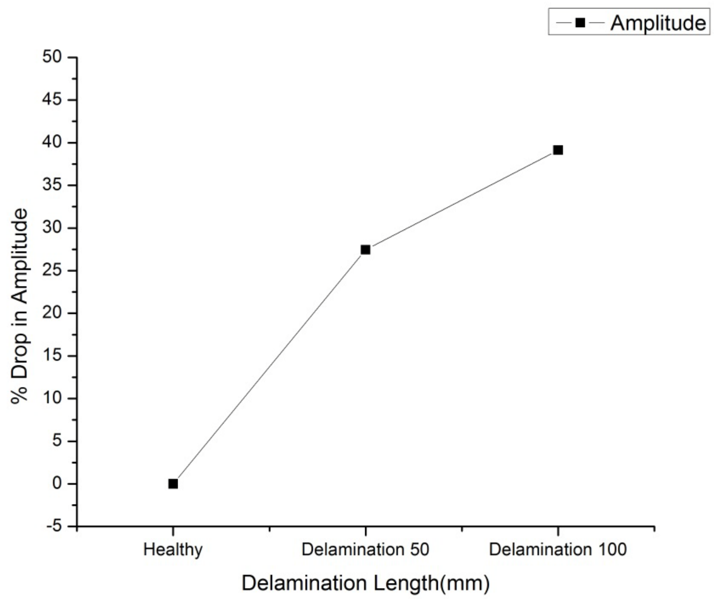


Fig. 5.24 Percentage drop in through signal amplitude at different delamination extend

Discussion

It was observed from above results that with use of right Frequency-angle combination, it is possible to detect the delamination in between laminate layers. There is drop of 27% in through transmission signature over delamination region having length of 50mm as compared to signature over healthy region. When delamination length has been increased to 100 mm then percentage drop in through transmission signature has been increased to 39%. This clearly indicate that with increase in delamination extent, there is drop in ultrasonic signal amplitude.

The region behind drop in signal amplitude is due to presence of multiple interfaces in delamination region. This act as hindrance in wave propagation, which results in dispersion & loss of ultrasonic signal.

5.4.1.4 Localization of delamination defect using Pulse-eco signatures at different locations

In through transmission technique, line scanning of composite plates has been done which indicate about presence of delamination defect. Further pulse-eco technique has been used to localize the delamination defect.

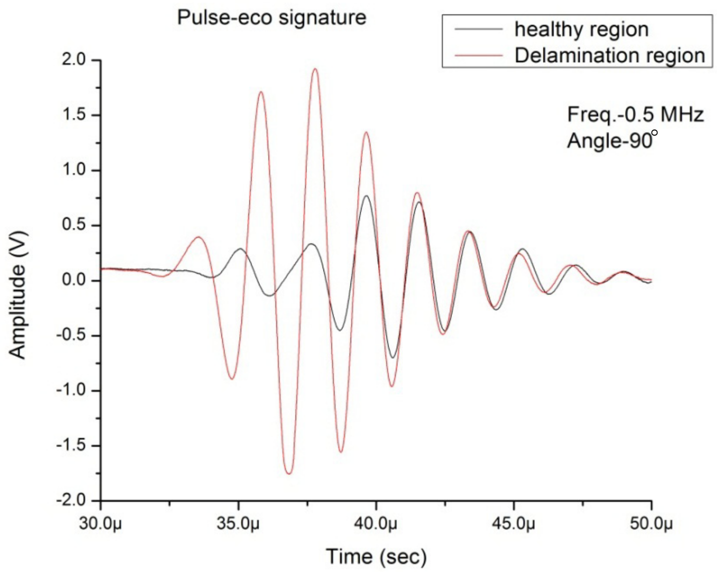


Fig. 5.25 Pulse-eco signature at different locations

It is quite evident from fig. 5.25 that pulse-eco signature over delamination region shows greater amplitude as compared to healthy region. This is due to reason that incident wave is reflected back from the delamination interface instead of passing throughout thickness and getting dispersed in the specimen. Regions with delamination defect indicated by fall in amplitude of pulse transmission testing, have been further probed by using pulse-eco technique & exact location of defect can be ascertained by reading location from the scanning set-up scale (fig. 4.22).

5.4.2 Exploring simulated delamination defects at different depths

In this delamination study, two delaminations of same size (100mm length) have been provided in three layer laminated specimen at different depth locations. One delamination called 2nd level delamination has been provided in between 1st& 2nd fibre layer whereas 3rd level delamination of same size has been induced in between 2nd& 3rd layer of glass fibre laminate specimen as shown in fig. 4.8 in chapter 4. Lamb waves with frequency 0.5 MHz have been used at different angle setting to determine the delamination at different depth of laminated specimens.

As different lamb wave modes are produced at different angles settings for particular frequency-thickness combination. Different modes detect defects in different layers of composites. So to detect defect in particular layer that particular mode need to be excited for defect evaluation

5.4.2.1 Through transmission signatures for 2nd level delamination detection

For detection of delamination at 2nd level various angle were tested & it has been found that with angle setting of 16° generate particular mode which has detected the delamination at 2nd level.

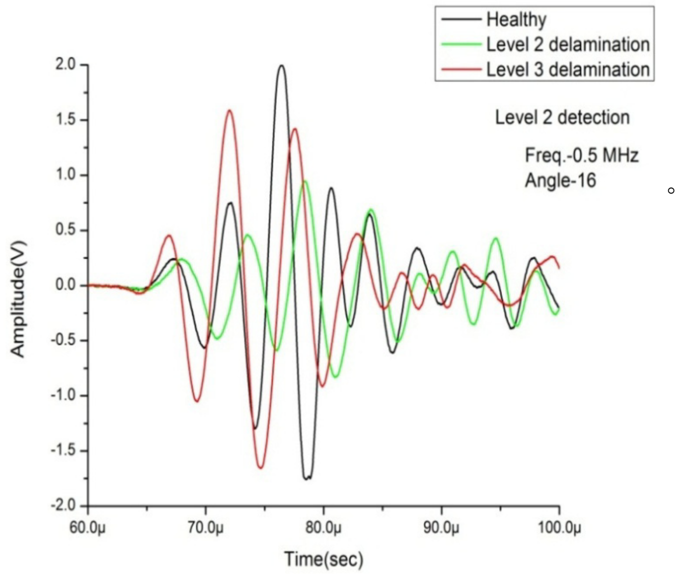


Fig. 5.26 Through transmission signature for 2nd level detection

5.4.2.2 Through transmission signatures for 3rd level delamination detection

For detection of delamination at 3rd level various angle were tested & it has been found that with angle setting of 29° generate particular mode which has detected the delamination at 3rd level.

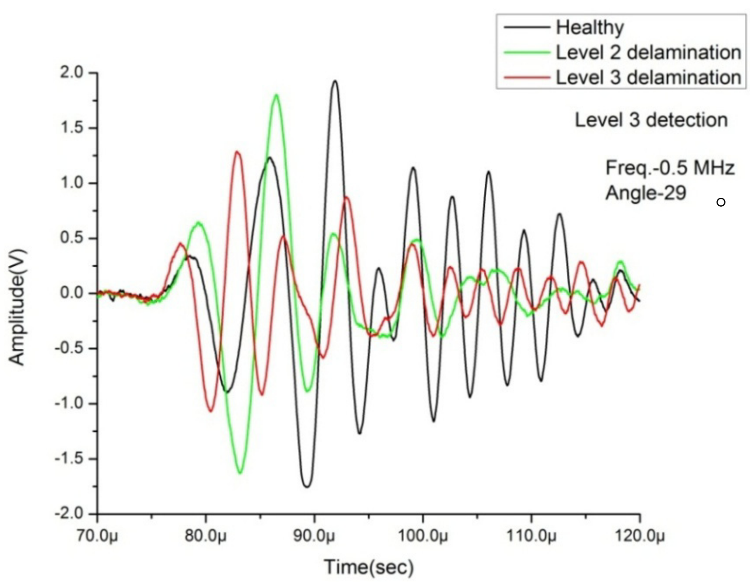


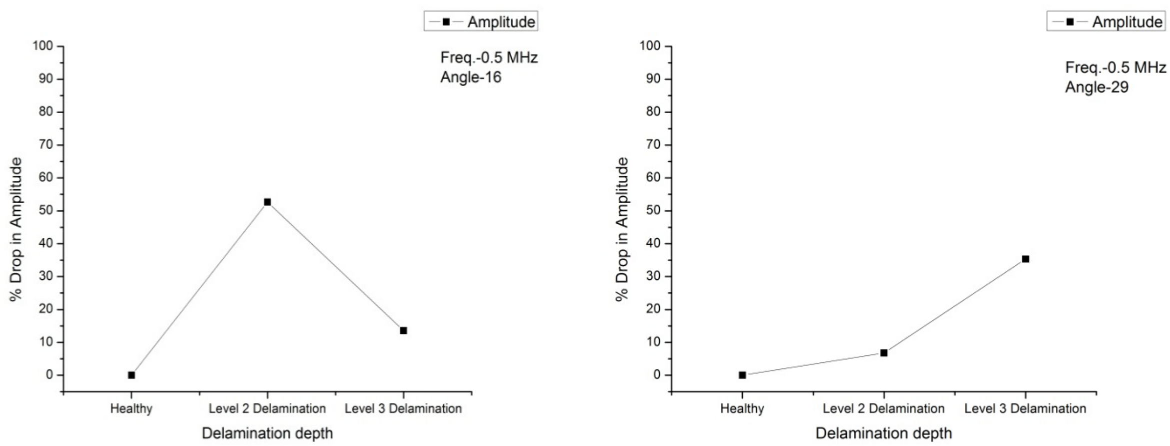
Fig. 5.27 Through transmission signature for 3rd level detection

5.4.2.3 Results of through transmission signatures for simulated delamination defects at different depths

Table 5.9 Through transmission signatures for simulated delamination defect at different depths

S.No.	Delamination level	Pk-Pk Amplitude (V)		% Decrease in Amplitude	
		Angle 16°	Angle 29°	Angle 16°	Angle 29°
1	Healthy	3.76	3.68	**0**	**0**
2	Level 2 delamination	1.78	3.43	**52.66**	**6.79**
3	Level 3 delamination	3.25	2.38	**13.56**	**35.33**

5.4.2.4 Percentage drop in through transmission signatures for simulated delamination defects at different depths



(a) **(b)**

Fig. 5.28 Comparison of through transmission signatures for simulated delamination defects at different depths at angle (a) 16° (b) 29°

Discussion

It has been observed from above graphs that right frequency-angle combination is helpful in determining the delamination in between different layers of laminated composite structures. Here it has been observed that with 0.5 MHz probe presented at 16° angle has shown significant change in peak-peak amplitude in pulse transmission testing of healthy zone and defective zone for specimen having defect at 2nd level as compared to defective region having similar defect at 3rd level.

Similarly when probe has been set at angle of 29° has shown significant change in peak-peak amplitude in pulse transmission testing of healthy zone and defective zone for specimen having defect at 3rd level as compared to defective region having similar defect at 2nd level.

This has reason behind that different amount of energy is injected by probe into different layers of laminate at different angle setting. Maximum energy flows into particular layer at particular angle. This energy of ultrasonic waves helps to determine the defect in that particular layer.

CHAPTER 6 CONCLUSION

From the experiment conducted following conclusions have been drawn:

6.1 Hygro-thermal damage evaluation

Ultrasonic guided waves are helpful to determine the health of specimen subjected to Hygro-thermal loading. Glass fibre laminate subjected to NaOH environment at 45°C had shown considerable loss in tensile strength (85%) & flexural strength (50%) after 30 days exposure to hygro-thermal loading conditions. Similar trend has been shown by through transmission signature which had dropped to 50 % of initial healthy signature. On the other hand there was not as much drop in tensile strength (30%) & flexural strength (15%) for water tank specimens after exposure for same duration. This was also depicted by guided wave signal amplitude. So it can be concluded that Ultrasonic guided waves can evaluate the damage caused to the laminated specimen subjected to hygro-thermal loading condition in terms of decrease in through transmission signature amplitude.

6.2 Mechanical damage evaluation

Glass fibre reinforced laminate specimen subjected to different percentage of ultimate tensile load in order to depict the in service load & stresses developed over time had shown detectable change in amplitude in through transmission signal. There was not much change in amplitude (11-13%) for specimen loaded with 25% & 50 % of peak load. This may be due to loading of specimens in elastic range. But for specimens loaded with 75% of ultimate tensile load had shown considerable loss in amplitude (about 20%) which was due to loading in plastic range which had caused fibre breakage, fibre pull-out, matrix cracking etc. This damage caused by tensile load has been evaluated with help of drop in guided wave signal amplitude.

6.3 Simulated delamination evaluation

Delamination study has shown that ultrasonic testing is able to evaluate delamination in between the layers of laminated specimen. From the experiment conducted it has been depicted that there was drop in through transmission signal (27%) over delamination length of 50mm as compared with healthy region. Further this drop increases to 39% with increase in delamination length to 100mm. Also Guided waves had determined the delamination in between different layers of laminated specimen at different depth. At different angles different modes have been generated which detected defects in between different layers. Delamination in between first & second layer of three layer laminate specimen has been detected at angle of 16° as there was drop of 53% in signal amplitude over delamination region as compared to healthy region. Whereas at angle 29°, delamination in between second & third layer was detected by comparing loss in amplitude (35 %) over delamination region as compared to healthy region.

So it has been concluded that ultrasonic guided waves can be used as NDT tool to predict the life of composite laminated plate structure by evaluating the loss in strength due to Hygro-thermal environment, actual loading conditions, delamination etc. by examining the loss in guided wave signal amplitude.

6.4 Scope of future work

1. Hygro-thermal experiment can be extended by use of more frequent durations & temperature conditions.
2. Sensitivity and selection of ideal modes for particular type of damage can be analytically evaluated & tested.
3. Delamination detection using guided waves on multi directional laminated composites with increased number of layer can be studied.
4. Damage caused to composite laminates by different loading conditions like fatigue loading, impact loading can be studied using guided waves.
5. The modeling and analysis of laminated composites subjected to ultrasonic testing can be done & compared with experimental results of laminated composites exposed do different type of damage.

REFERENCES

[1] www.metals.about.com/library/bldef-Composite-Material.htm

[2] www.composite.about.com/od/aboutcompositesplastics/l/aa060297.htm

[3] www.dtic.mil/ndia/2002artillery/gorman.pdf

[4] www.substech.com/dokuwiki/doku.php?id=classification_of_composites

[5] www.wikipedia.com/Composite material.html

[6] Fibre reinforced polymers by P.K Mallick (2007),CRC press, New york

[7] www.emba.uvm.edu/iatridis/me257/Introduction.html

[8] Methods of detecting defects in composites rehabilitated concrete structures by Vistasp M. Karbhari, (2005), final report, Department of Structural Engineering, University of California, San Diego.

[9] Qiang G.,Wanxie Z. and Howson W. (2004), "A precise method for solving wave propagation problems in layered anisotropic media", *Wave Motion*,40, pp.191–207

[10] www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Introduction/description.htm

[11] Qiao P., Lu K. & Lestari W. (2008), "Combined Static/Dynamic Technique for Damage Detection of Laminated Composite Plates", *Experimental Mechanics*, 48, pp.17–35

[12] Transducers for ultrasonic flaw detection by V.N.Bindal (1999)

[13] Demcenko A. and Mazeika L. (2002), "Calculation of Lamb waves dispersion curves in multi-layered planar structures", *ISSN 1392-2114 ULTRAGARSAS, Nr. 3(44),* pp.15-17.

[14] Yang W. and Kundu T. (1998), "Guided waves in multilayered plates for internal defect detection", *Journal of Engineering Mechanics*, 124(3), pp.311-318.

[15] Seale D., Smith B. and Prosser W. (1998), "Lamb wave assessment of fatigue and thermal damage in composites", *Acoustical Society of America,* 103, 5(1), pp. 2416-2424

[16] Kessler S., Spearing S. and Soutis C. (2001), "Optimization of Lamb wave methods for damage detection in composite materials", *Structural Health Monitoring,* third edition, Technomic Publishing Company, Lancaster.

[17] Kundu T, Potel C and Belleval J. (2001), "Importance of near lamb mode imaging of multilayered composite plates", *Ultrasonics 39,* pp.283-290.

[18] Kessler S. and Spearing S. (2002), "Damage detection in composite materials using Lamb wave methods", *Smart Materials and Structures*, 11, pp. 269–278.

[19] Sevostianov I., Verijenko V., and Verijenko B. (2003), " Evaluation of microstructure and properties deterioration in short fiber reinforced thermoplastics subjected to hydrothermal aging", *Composite Structures*, 62, pp. 409–415.

[20] Hay T., Wei L. and Rose J. (2003), "Rapid Inspection of Composite Skin–Honeycomb Core Structures with Ultrasonic Guided Waves", *Journal of composite materials*,37(10), pp.929-938

[21] Zhang, Z. and Richardson M. (2004), "Visualisation of barely visible impact damage in polymer matrix composites using an optical deformation and strain measurement system*", Composites* 36, pp.1073–1078.

[22] Demcenko A., Zukauskas E., Kazys R., and Voleisis A.(2005),"Investigation of interaction of the Lamb wave with delamination type defect in glare composite using air-coupled ultrasonic technique", *Forum Acusticum, Budapest,* pp.2817-2822.

[23] Edalati K., Kermani A., Naderi B. and Panahi B.(2005), "Defects Evaluation in Lamb Wave Testing of Thin Plates", *Middle East Nondestructive Testing Conference & Exhibition,* 27-30 Nov 2005 Bahrain, Manama.

[24] Zhang H., Fan S., Liu Z. and Lu D. (2006), "The effect of fiber orientation on lamb wave propagation in layered anisotropic composite plates", *IEEE Ultrasonics Symposium*, 21, pp.1821-1823

[25] G. Wrobel, S. Pawlak [2006], Ultrasonic evaluation of the fibre content in glass/epoxy composites", *Journal of Achievements in Materials and Manufacturing Engineering* 18(1-2), pp.165-170

[26] Berketis K., Tzetzis D. and Hogg P. (2007), "Non-Contact Ultrsonics used for impact damage detection of long-term water immersed GFRP composites", *4th international conference on NDT,* 11-14 Oct. 2007, chania, Greece.

[27] Su Z., Wang X., Chen Z. and Ye L. (2007), "A hierarchical data fusion scheme for identifying multi-damage in composite structures with a built-in sensor network", *Smart Material Structure* 16 , pp. 2067–2079

[28] Xue Qi X., ROSE J. and Xu C. (2008), "Ultrasonic guided wave nondestructive testing for helicopter rotor blades",*17th World Conference on Nondestructive Testing*, 25-28 Oct 2008, Shanghai, China.

[29] Raisutis R., E.Jasiuniene E. and Zukauskas E.(2008), "Ultrasonic NDT of wind turbine blades using guided waves",*ISSN 1392-2114 ULTRAGARSAS,*63(1), pp.7-11

[30] Wrobel G. and Kaczmarczyk J. (2009), "Numerical simulation of fatigue degradation process of polymer materials using diagnostic acoustic characteristics", *Journal of Achievements in Materials and Manufacturing Engineering,* 36(2), pp.168-175

[31] Nadella K, Ken Salas K, and Cesnik C. (2010), "Characterization of Guided wave Propagation in Composite Plates", *SPIE,* 7650, 76502H, pp. 1-12.

[32] Wrobel G. and Kaczmarczyk J. (2009), "Numerical simulation of fatigue degradation process of polymer materials using diagnostic acoustic characteristics", *Journal of achievements in materials and manufacturing engineering ,*36/2, pp. 154-160

[33] David J. Collins, Thesis report on damage detection in composite materials using acoustic emission and self-sensing fibres.

[34] Pradhan B. and Chakraborthy D. (2002), "Fracture behavior of FRP composite laminates with embedded two interacting delaminations at the interface", *Journal of reinforced plastics and composites*,21, pp.681-698

[35] By Anthony Kelly, Concise Encyclopedia of Composite Materials.

[36] Roy R. and Sarkar B. (2001), "Behavior of *E*-glass fibre reinforced vinyl ester resin composites under impact fatigue", *Indian Academy of Sciences,* 24(2), pp. 137-142.

[37] Jungert A. (2008), "Damage Detection in Wind Turbine Blades using two Different Acoustic Techniques", *The e-Journal of Nondestructive Testing*, pp. 1-10

[38] Banerjee S and Kundu T. (2007), "Modeling ultrasonic wave scattering by internal anomalies for structural monitoring" SPIE.

[39] G. Wrobel. and S. Pawlak [2006], Ultrasonic evaluation of the fibre content in glass/epoxy composites (JAMME vol. 18 Issue 1-2).

[40] Sevostianov I., Verijenko V. and Verijenko B. (2003), "Environmental degradation using functionally graded material approach", *Composite Structures*,62, pp.417–421

[41] Sharma A. (2009), "Environmental degradation of GFRP" M.E thesis submitted to mechanical engineering department, Thapar University, Patiala.