

**HYGRO-MECHANICAL BEHAVIOUR OF FIBRE MATRIX  
LAMINATES FOR DIFFERENT FIBRE ORIENTATIONS**

*A Thesis Submitted in Fulfilment of the Requirement for the Award of the Degree of*

MASTER OF ENGINEERING

in

CAD/CAM Engineering

Submitted by

SANDEEP VATS

801684012

Under Supervisions of

**Dr. Deepak Jain**

Assistant Professor, MED

**Dr. Tarun Kumar Bera**

Associate Professor, MED



**THAPAR INSTITUTE**  
OF ENGINEERING & TECHNOLOGY  
(Deemed to be University)

MECHANICAL ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING & TECHNOLOGY  
(A DEEMED TO BE UNIVERSITY), PATIALA, PUNJAB  
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## DECLARATION

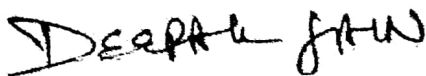
I, Sandeep Vats hereby declare that the work presented in this thesis entitled, "Hygro-Mechanical Behaviour of Fibre Matrix Laminates for Different Fibre Orientations" in fulfilment of the requirement for the award of degree of Master of Engineering (ME CAD/CAM) submitted at Mechanical Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of Dr. Deepak Jain, Assistant Professor, and Tarun Kumar Bera, Associate Professor, Mechanical Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala. The matter presented in this thesis has not been submitted either in part or full to any other university or institute for the award of any other degree.

Date: 13/7/2018



(Sandeep Vats)

(801684012)



Dr. Deepak Jain  
Assistant Professor  
Mechanical Engineering Department  
Thapar Institute of Engineering & Technology  
(A Deemed to be University)  
Patiala, Punjab

Date: 13/7/18



Dr. Tarun Kumar Bera  
Associate Professor  
Mechanical Engineering Department  
Thapar Institute of Engineering & Technology  
(A Deemed to be University)  
Patiala, Punjab

Date: 13/7/18



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*Sandeep  
Vats.*

Sandeep Vats

Roll No.: 801684012



## ABSTRACT

Composite materials have the versatility in their properties which enables them to be applied in large number of fields. Fibre Reinforced Polymers (FRPs) mainly have large advantages over conventional metals. FRPs are found to be sensitive to the hot and humid environments. Under these environmental conditions, moisture absorption in FRPs causes deterioration and can limit their lives considerably during in-service applications. In this study, the moisture diffusion kinetics inside the FRPs with angle and cross ply orientations are investigated. In particular, the effects of different fibre orientations have been investigated on both moisture diffusion and moisture diffusion induced stresses. Different analytical as well as experimental work is carried out for the investigation. A micromechanical model of three-dimensional fibre polymer matrix composites is modelled using FEA (Abaqus) and bond graph elements (Symbols Shakti). Fick's law based moisture diffusion analysis is conducted to analyze the effect of fibre orientations on the moisture diffusion process. It is also observed that moisture diffusion in FRPs leads to development of stresses. The stresses are developed in composites due to moisture absorption with displacement boundary conditions. Therefore, different displacement boundary conditions according to concentric cylinder assemblage and plane strain boundary conditions are applied to study the effect of moisture absorption and different displacement boundary conditions on the stresses induced. It is seen that cross ply orientations have better moisture barrier properties and stress behaviour as compared to the other orientations with similar fibre matrix volume fractions. All the results are validated using some widely used theories of composite micromechanics.

*Keywords:* Fibre Reinforced Polymers (FRPs), Moisture Diffusion, Fick's Law, Hygro-mechanical Analysis, FEA, Bond graph Modelling, Experiment



## LIST OF ACRONYMS

FRP ≡ Fiber Reinforced Polymer

FEA ≡ Finite Element Analysis

CCA ≡ Concentric Cylinder Assemblage

RVE ≡ Representative Volume Element

ECF ≡ Edge Correction Factor



## NOMENCLATURE

$A$	Area
$c$	Concentration
$C$	Compliance
$C_{\text{amb}}$	Ambient Concentration
$C_p$	Specific Heat
$D_{\text{eff}}$	Effective Diffusivity
$D_f$	Diffusivity of fibre
$D_m$	Diffusivity of matrix
$D_t$	Thermal Diffusivity
$e$	Effort
$E$	Young's Modulus
$f$	Flow
$G$	Shear modulus
$GY$	Gyrator
$I$	Inertial
$\bar{J}$	Diffusion Flux
$k$	Thermal Conductivity
$L$	Length
$m$	Mass gain
$\dot{m}$	Mass flow rate
$M$	Mass Concentration
$M_t$	Saturated Volume at time (t)
$M_\infty$	Saturated Volume at time (t= $\infty$ )
$r$	Radial Coordinate
$R$	Dissipator
$SE$	Source of effort
$SF$	Source of flow
$T$	Time
$TF$	Transformer
$u$	Displacement in x direction
$v$	Displacement in y direction
$V_f$	Fibre Volume Fraction
$V_m$	Matrix Volume Fraction
$w$	Displacement in z direction
$x$	Saturated length
$z$	Vertical Coordinate
$\beta_f$	Coefficient of moisture Expansion of fibre
$\beta_m$	Coefficient of moisture Expansion of matrix
$\gamma$	Lame's Constant
$\varepsilon$	Strain
$\theta$	Angular Coordinate
$\mu$	Modulus

$\nu$	Poisson's Ratio
$\rho$	Mass density
$\sigma_f$	Axial stress in fibre
$\sigma_m$	Axial stress in matrix

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# CHAPTER 1

## INTRODUCTION

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Introduction of new materials is really important in the development of whole civilization. From the Stone Age, people started using materials for their daily use like wood, stones *etc.* After the development of materials science, different types of materials were invented in different fields. After further development in materials science, science of producing alloys was invented further giving a new scope to research in the field of materials. In recent times, in spite of using only alloys, a new category of materials were developed called composite materials. The composite materials are different from alloys and are also manufactured in different ways compared to ways alloys are manufactured.

### 1.1 INTRODUCTION TO COMPOSITES

The composite materials are defined as combinations of macro constituents that can be easily seen with naked eye and have distinct interface between them. The composite materials are designed to eliminate the problems while using of conventional metals. Composite materials are not only considered for their structural properties but also have better thermal, electrical and environmental applications. The properties of composite materials can easily be controlled using different types of materials according to the properties required.

#### 1.1.1 Types of Composites

Composite materials have a wide scope in the field of engineering. Any two or more materials combined together in a particular form leads to manufacturing of composite materials. As there are large numbers of different types of materials available, therefore, different types of combinations of materials can be developed according to the desired properties required. Composites materials can be polymer matrix, metal matrix composites, ceramic matrix composites *etc.* Figure 1.1 shows different types of composites used in industries, buildings *etc.*

- a) *Polymer matrix composites*: These are the composite materials in which various types of long and short fibres are embedded into the polymer matrix. These are basically designed to transfer loads between fibres and matrix. Polymer matrix composites (PMC) are mostly light in weight and have high stiffness and high strength. PMCs

contain 60% of fibre as reinforcement. Matrix of the PMCs helps PMCs to resist impact damage, humid environmental conditions and chemical effect *etc.*

- b) *Metal matrix composites*: Metal matrix composites (MMCs) are the composite materials which definitely have a metal as a constituent and other constituents are not necessarily being metals. Reinforcement in metal matrix composites can be coated with a material so that they cannot react with the matrix. When metal matrix is used for structure applications, light weight matrix is used like aluminium which provides support to the reinforcement. When MMCs are designed for high temperature regions, alloys like cobalt, nickel are used as matrices.
  
- c) *Ceramic matrix composites*: Ceramic matrix composites (CMCs) are the composite matrix in which fibres as well as matrix are ceramic. CMCs are very prone to fractures due to presence of small cracks in CMCs. Reinforcement helps in increasing strength of CMCs and mainly CMCs have ceramic fibres embedded in them. Here, fibres provide more strength contrary to PMCs and MMCs where fibres are more prone to failure. Carbon-carbon composite is one of the common CMCs.

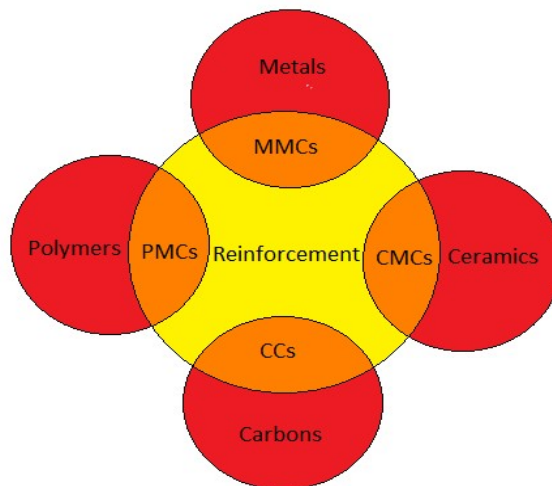


Figure 1.1 Classification of composites

### 1.1.2 Different Phases of Fibre Matrix Composites

Composite materials have two or more phases depending on the number of constituent materials. Phases in composite materials are defined as the region where density of one type of material is very large in comparison to other and the phase where different constituents

are present in same ratio is called inter-phase which basically lies at the boundaries of different materials. Figure 1.2 represents different phases in composites.

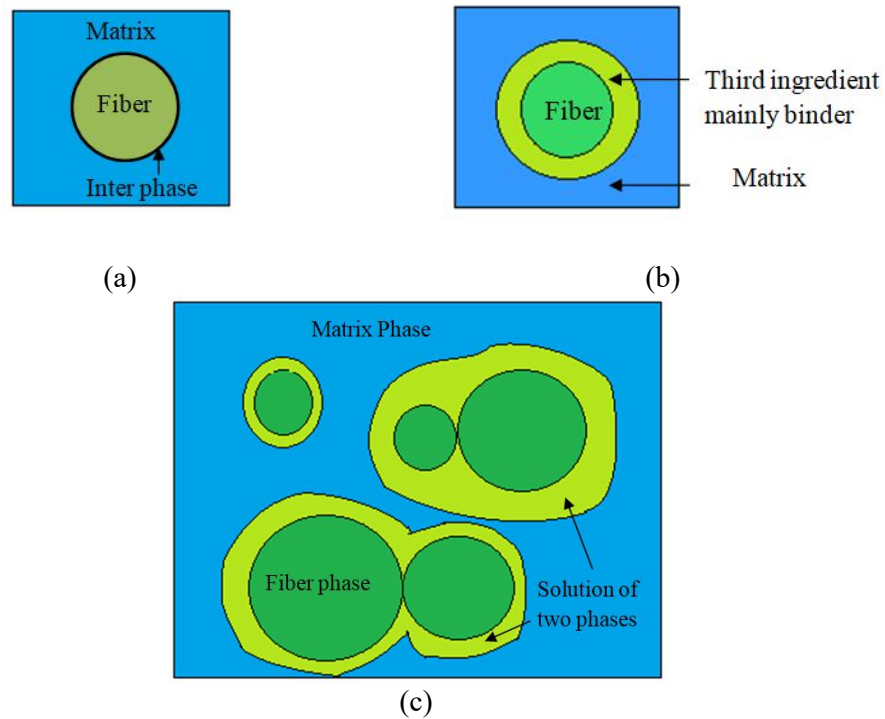


Figure 1.2 Different phases of composite materials: (a) two phases with thin line of inter-phase (b) different material as inter phase and (c) solution of matrix and fibre as inter phase

- a) *Matrix phase*: This is the phase in composite materials with continuous phase. This phase is uniform all around the composite materials. This is the phase that is more ductile and is less hard in comparison to the reinforcing phase. The main characteristic of matrix phase is to hold the reinforcing phase and share load with it.
- b) *Dispersed phase (Reinforcing phase)*: This phase includes materials that are embedded in the matrix and as the name suggests this phase is not uniform throughout the material. This phase provides more strength in comparison to the matrix phase, therefore, it is called the reinforcing phase.
- c) *Inter-phase*: This is the phase which is the mixture of matrix and reinforcing phase or sometimes inter-phase includes some different material other than reinforcing and matrix material. It differentiates the two materials and acts as a binder between the two materials.

### 1.1.3 Factors Affecting Fibre Matrix Composite Properties

The concept of composite material was mainly developed because properties can easily be controlled and by using different types of fibres as reinforcing phase and using different materials as matrix phase. Factors that control the properties of composite materials are change in direction of fibres, fibre volume fraction, change in shape of fibres, moisture ingress *etc.*

- a) *Change in concentration of reinforcing phase:* Concentration of reinforcing phase plays a key role in deciding the properties of the composite materials. As when the volume fraction of fibre increases in the composite materials it provides more strength to the structure and also reduces the mass flow rate in terms of moisture into the composite materials if the fibres have less diffusivity in comparison to the matrix phase material.
- b) *Change in shape of the reinforcing material:* Change in shape of the reinforcing materials change the flow of moisture flow in the composite materials at the micrometers level thus affecting the mass flow rate through the composite materials.
- c) *Change in the orientation of the fibre:* Change in fibre orientation drastically changes the properties of the composite material. Fibres in the direction of the load acting can share the load to large extent in comparison to fibre kept in direction perpendicular to the acting load. Thus, leading to failure of structures. Figure 1.3 represents three-dimensional of fibre matrix composite with different fibre orientations.

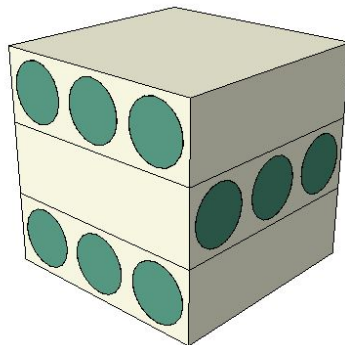


Figure 1.3 Different fibre orientations

- d) *Moisture degradation:* When composite materials are exposed to hot humid environmental conditions, moisture absorption takes place in composite materials. In

composite materials like carbon fibre reinforced composites, moisture absorption takes place only in epoxy material, thus leading to difference in volumetric expansion due to moisture absorption. Different levels of expansion in carbon fibre in comparison to epoxy leads to development of local stresses in the interface region of fibre and epoxy. The resultant of these induced stresses is the reason behind degradation in composite materials, thus, decreasing their strength and durability. Figure 1.4 and Figure 1.5 show the degradation in composites caused due to moisture ingress.

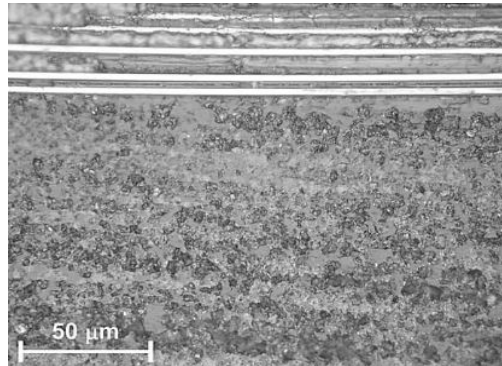


Figure 1.4 Degradation in carbon reinforced composite with moisture for 1000 h [1]

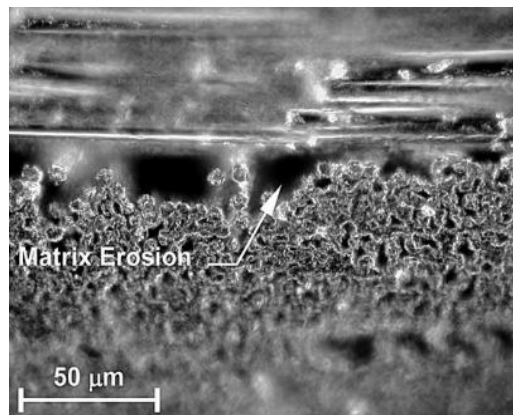


Figure 1.5 Degradation in carbon reinforced composite with moisture for 2000 h [1]

#### 1.1.4 Potential Applications

In recent years, demands of performance from materials are unlimited and these demands cannot be met by one material, therefore, two or more materials are joined together. Materials required should be light in weight, should have high strength and should be durable. Composite materials having all these properties have applications in robotics,

aerospace, racing car industries, military equipments *etc.* Figure 1.6 shows different sectors of composites applications.

- a) Composites are mainly used in surface transportation because surface transporters are large in size and there is flexibility for the changes in design, materials and way of production.
- b) In heavy transport vehicles composites are used to manufacture their parts as they are light and strength to weight ratio is really good.
- c) Thermo set composites are mainly found in electrical transformers and switch gears because of their ability to sustain harsh environments.
- d) In spacecraft, antenna, solar reflectors, rocket engines *etc.* are the places where composite materials are used.
- e) Aircraft turbine blades, airfoil surfaces, engine bay doors, rotor shafts in helicopters *etc.* are made from toughened carbon fibre reinforced plastic which is the most widely used composite materials.
- f) Wind turbines blades is also one of the key application of composite materials where biodegradable as well as non biodegradable composites are used for manufacturing of blades. Carbon wood epoxy is the composite used in wind turbine blade manufacturing.
- g) Composite materials like cemented carbides are used in making cutting tools, for dies, powder metallurgy *etc.*
- h) For high temperature application titanium carbide cermets are used for parts like gas turbine nozzle vanes valve seats cutting tools for steels gauge blocks, bearing seal rings, valve liners *etc.* are made up of chromium carbide cermets.
- i) Cosmolite thermoplastic fibre reinforced composite is used to manufacture shells and dupont surlyn film which is an impact resistant coating used for golf balls.

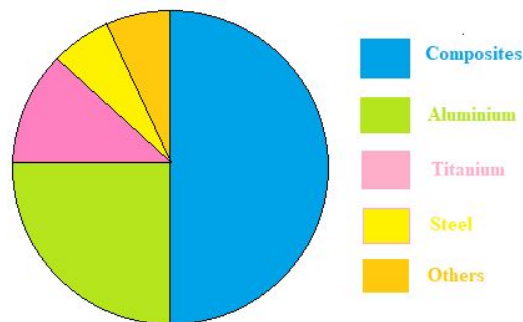


Figure 1.6 Applications of composite materials in aerospace industry

### 1.1.5 Advantages and Disadvantages

The idea of composite materials came into play because the desirable properties needed by industries couldn't be met by conventional metals. Composite materials consists of two or more materials .Therefore their properties can be easily controlled. Figure 1.7 shows different properties of composites that are better than conventional materials.

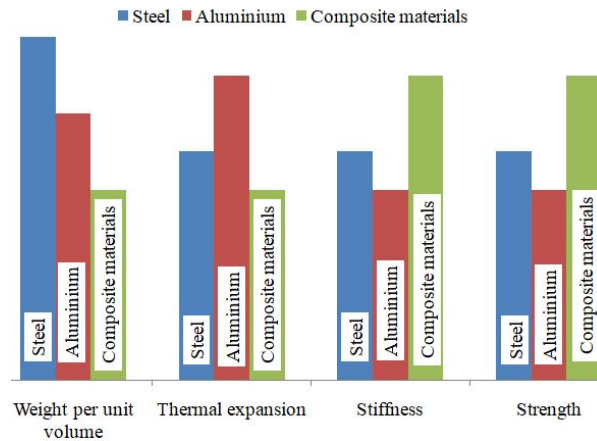


Figure 1.7 Comparison of properties of composite materials with different metals

Basically industries like aero space, car and military equipments industries require materials that provide with high strength, high stiffness, less in weight per unit volume and less thermal expansion *etc.* Despite of having long list of benefits of composite materials but still there are many aspects where composite materials lag far behind in comparison to conventional materials. Figure 1.8 shows some of the disadvantages of composite materials that are encountered. Composite materials are more brittle, cost high, have more fabrication complexity and are more vulnerable to moisture exposure.

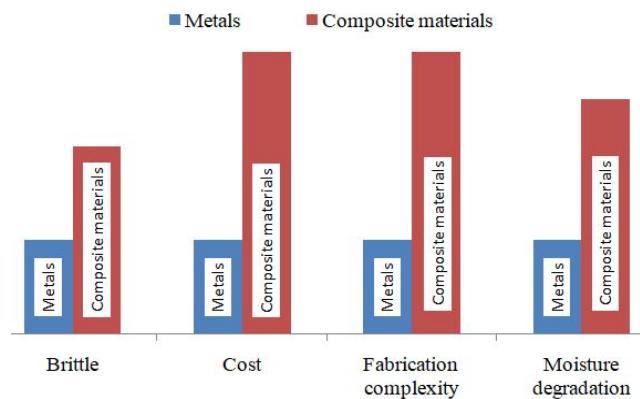


Figure 1.8 Comparison of composite materials with metals

## 1.2 INTRODUCTION TO FIBRE REINFORCED POLYMERS (FRPs)

Fibre reinforced polymer (FRPs) are plastics that are embedded with fibre that can be of glass, carbon or aramid other fibres like pine ,wood or asbestos can also be used. Polymers used are mainly epoxy, vinyl ester or polyester thermo setting plastic and phenol formaldehyde resin. Failure of FRPs takes place when fibres exhibit deflection in lateral or sideways direction which is called fibre buckling. Transverse strength of FRPs mainly depends on strength of fibre and matrix and that depends on properties of fibre and matrix.

### 1.2.1 Types of Fibre Direction in FRPs

- a) *Unidirectional fibres*: This is the type of fibre reinforcement when all the fibres are aligned in only one direction. Unidirectional orientations of fibre reinforcement helps in creating composite with extremely strong and light weighing parts that provide maximum strength in only one direction.
- b) *Bidirectional fibres*: This is the type of fibre reinforcement when the fibres are oriented in two directions. FRPs having bidirectional fibre reinforcement found to have lower values of tensile in comparison to fibre with unidirectional fibre reinforcement orientation.
- Cross ply: this is the fibre reinforcement when constituting fibres are oriented in two directions and these two directions are perpendicular to each other.
  - Angle ply: fibre reinforcement when constituting fibres are oriented in two direction and these two directions are at an angle to each other. Figure 1.9 represents different fibre orientations.

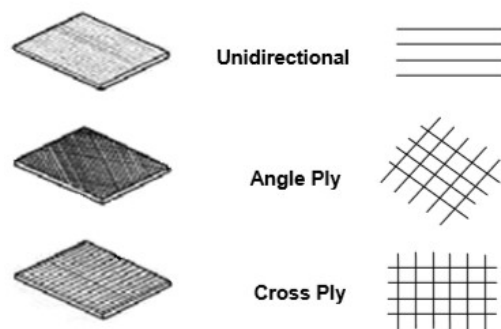


Figure 1.9 Different fibre orientations [2]

## 1.2.2 Types of Fibres

The structural performance that is required from the composite material is mainly provided by the fibre reinforcements. There are various types of fibre reinforcements available with various chemical forms that mainly control desirable properties of composite materials.

### (a) *Glass Fibres*

- **E-Glass Fibres:** These are electrical grade fibres. E-Glass fibres are mainly developed for standoff insulators. The alkali content in these fibres is very less. E-Glass fibre require less expenses during manufacturing and there production rate is very high. Some of the advantages of using E-glass fibres are that they provide high strength, high stiffness and have good chemical resistance.
- **C-Glass Fibres:** C-Glass fibres were designed to resist chemical attack that can destroy E-Glass fibres. These fibres are also used as thin outside film at the places that are more exposed to moisture and water. Figure 1.10 shows glass fibre roll and glass fibre woven fabric.



(a)



(b)

Figure 1.10 (a) Glass fibre rolls (b) woven fabric of glass fibre [2]

- **R, S or T glass Fibres:** These fibres are named according to their use, as R- Glass fibres are used for reinforcements, S-Glass fibres are used as stronger and stiffer version of E-Glass, but R- Glass fibres have high cost of manufacturing and have relative low fatigue resistance. T - Glass fibres are used as thermal insulators.

(b) *Aramid (kelvar) Fibres:* Aramid fabrics are heat resistant in nature. These are strong symmetric fibres that are used for military vehicles especially where ballistic rated body armour fabric and ballistic properties are needed. These fibres are resistant to abrasion and

even to high temperatures. One of the important factors is that they have no melting point but are sensitive to acids and different salts. Figure 1.11 shows aramid fibres roll.



Figure 1.11 Aramid fibres roll [2]

(c) *Carbon Fibres*: These fibres are 10 microns in diameter. Carbon fibres provide high stiffness, high tensile strength. They have low weight and high chemical resistance as the carbon-carbon bond is very stable. Carbon fibres likely as aramid fibres have high temperature tolerances and are used for making car bodies. Figure 1.12 shows carbon fibres roll.



Figure 1.12 Carbon fibres roll [2]

### 1.2.3 Types of Resins

Composites consist of fibres as reinforcement and resin as matrix. Resins help in transferring of mechanical loads to the reinforcing fibres and to the rest of the composite structures. Resins act as binder and keep the fibres bounded together. Resins provide protection to fibres against environmental and mechanical damage. Resins are mainly divided into two categories: (i) Thermo sets (ii) Thermoplastics

- a) *Thermo-set Resins*: These are the most commonly used resins. Thermo set resins undergo a process called polymerization under which liquid gets converted into solid and becomes hard enough to provide support to fibres. Curing of thermo sets is done

with the use of heat, catalyst or both. After curing, thermo set resins can never be converted back into their original liquid form. Figure 1.14 shows cross linking in thermosetting polymers. Some of the common thermo sets are: (i) Epoxy (ii) Vinyl ester (iii) Phenolic (iv) Polyester (v) Polyurethane

- Epoxy: Epoxy resins are widely used for fabrication of various composite structures, and for concrete repair. Epoxy resins have lower shrinkage in comparison to unsaturated polyester resin. Epoxy resins can be very easily formulated with different materials or with other epoxy resins to achieve desired performance features. These resins have good mechanical properties, superior electrical properties and good resistance to harsh environments. Epoxy resins have good performance even at high temperatures.
- Polyester: The polyester has main advantage that they can be used to balance the properties, cost and dimensional stability of composites. Polyesters hold 75% of the total resins used.
- Vinyl ester: Vinyl esters are formed after reaction of acrylic acid with epoxy resin. Corrosion resistance and mechanical toughness are offered by vinyl esters. These are developed so that all the advantages of the epoxy resin can be combined.
- Phenolic: These are thermosetting resins that release water on curing after condensation. They are highly resistant to high temperature and have high sound damping characteristics.
- Polyurethane: The basis of polyurethane is the exothermic reaction of organic polyisocyanates with polyols. These are mainly used for coating purposes or as adhesive as they are highly flexible, tough and get cured really fast. These are also used in tyres and there adhesive bonds have good resistance to impacts.

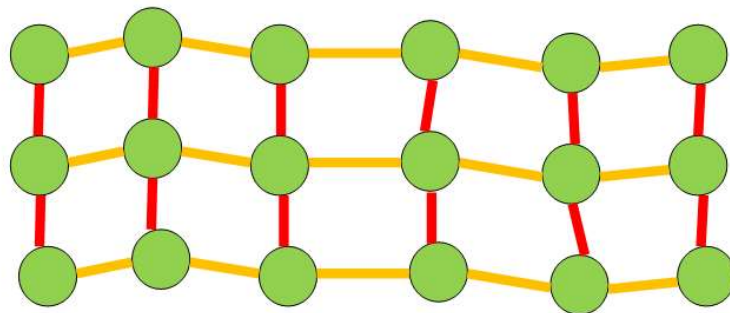


Figure 1.13 Cross linking of thermo sets during curing process

b) *Thermoplastic Resins*: These are not cross linked resins that can be melted and can be formed again and again. These are characterised as polycarbonate, polyethylene, polystyrene and ABS. Figure 1.14 represents pictorial representation of thermoplastic resins.

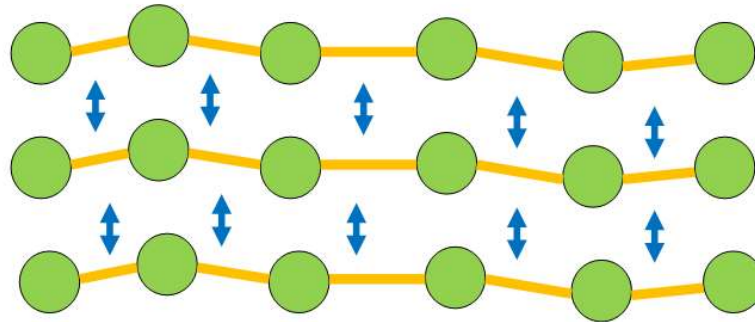


Figure 1.14 Thermoplastics strong within the chain but no cross linking

### 1.3 INTRODUCTION TO BOND GRAPHS

In 1959, bond graph modelling was invented by H. M Paynter. Bond graph modelling is a graphical representation of trading of powers between two interconnected parts within a system. Bond graph representation helps in presentation of hydraulic, electrical, mechanical *etc.* systems without actually changing their spatial arrangement. One of the unique features of bond graph modelling is the two ways flow of power mainly called as flow and effort decided after analysing relationship between cause and effect.

For modelling a system using this approach, initially effort and flow are decided within the system, then subsystems are decided through which power exchange takes place and later elements that can represent the particular subsystem are identified. Using this process any type of system can be designed thus it is called universal approach.

Bond graph uses compliance (C), inertial (I), dissipater (R), source of flow (SF), source of effort (SE), gyrator (GY) and transformer (TF) elements as basic standard elements. All these elements are connected using bonds. It is the bond that helps in providing a channel for transfer of power and act as carrier of flow as well as effort information.

**Table 1.1** Effort and flow variables in different energy domains [3]

Systems	Effort ( $e$ )	Flow( $f$ )
Thermal	Temperature	Entropy Flow Rate
Thermal/ Hydraulic	Pressure	Volume Flow Rate
Electrical	Voltage	Current
Mechanical	Force	Velocity
	Torque	Angular Velocity
Magnetic	Magneto-motive Force	Magnetic Flux
Chemical	Chemical Potential	Molar Flow Rate
	Enthalpy	Mass Flow Rate

### 1.3.1 Basic 1 port elements

These are defined as single power port elements. At these elements only one pair of flow and effort variables are present. There are two types of ports, active and passive ports. Active port elements are the elements having power source. Source of flow and source of effort are active port elements. Passive ports elements are the elements having no power source. Resistor, inductor, capacitor are passive port elements.

- Compliance elements: Compliance elements are the energy storing elements and are denoted by 'C'. They represent effort as time integral of flow. Accumulator in hydraulic systems and capacitor in electrical systems are some examples of compliance elements. In bond graph lexicon a spring with stiffness  $K$  is represented as Figure 1.15.

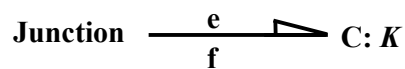


Figure 1.15 Depiction of compliance elements in bond graph lexicon

$$F = k.x \quad (1.1)$$

$$e = k \times Q \quad (1.2)$$

$$e = k \int_{-\infty}^t f(t) dt \quad (1.3)$$

Equation 1.2 and 1.3 depicts integral cause and effect relationship where flow ( $f$ ) input and effort ( $e$ ) is output from element.

- Inertial elements: Inertial elements are the second energy storing elements in the bond-graph lexicon represented by ‘I’. Inertial elements are used to model inductance effects and inertial effects in electrical and mechanical systems respectively. Figure 1.16 represents the graphical representation of mechanical system with mass  $m$ .

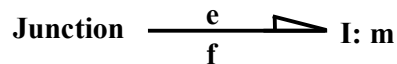


Figure 1.16 Depiction of inertial elements in bond graph lexicon

$$F = m\ddot{x} = m \frac{\partial f}{\partial t} \quad (1.4)$$

$$f = \frac{1}{m} \int_{-\infty}^t e dt \quad (1.5)$$

Equation 1.4 and 1.5 depicts integral cause and effect relationship of the inertial element with flow as result and effort as the source of cause.

- Resistive elements: Resistive elements denoted by ‘R’, act as resistance or obstruction for electrical mechanism and mechanical dampers for mechanical system. Inductive or resistive may be cause and effect of resistive elements and it is represented graphically as Figure 1.17.

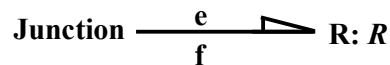


Figure 1.17 Depiction of resistive element in bond graph lexicon

$$F = R\dot{x} \quad (1.6)$$

$$e = R.f \quad (1.7)$$

Equation 1.6 and 1.7 depicts effort as the output from the resistive element, which represents resistive cause and effect relationship in the junction side.

- Source of flow: ‘SF’ character is used to represent source of flow in bond graph language. A half arrow pointing towards the junction or system away from source of flow defines source of flow. This port is the active port .displacement, current  $n$ , and

volume flow rate are the examples of source of flow in mechanical, electrical and hydraulic systems respectively. Graphical representation of electric current in electrical domain is given in Figure 1.18.



Figure 1.18 Depiction of source of flow in bond graph lexicon

- Source of effort: ‘SE’ character is used to represent source of effort in bond graph lexicon. A half arrow pointing away from the source of effort defined as input to the system in terms of external force. This port is the active port and force or torque, electric potential and hydraulic pressure are the example of source of effort in mechanical, electrical and hydraulic systems respectively. Figure 1.19 represents source of effort to any system as voltage is a source of effort for the electrical system.



Figure 1.19 Depiction of source of effort in bond graph lexicon

1.3.2 Two port elements

Transformer and gyrator are two port elements. In bond graph language they are denoted as ‘TF’ and ‘GY’. These are the elements that are connected with two pairs of flow and effort.

- Transformer: Transformer is the element that does not store, create or destroy energy. it helps in scaling or de-scaling of power . In mechanical system transformers mass less rigid lever and in electrical domain it is an electrical transformer. In bond graph it converts one type of flow to another type of flow and same is the case with effort transfer. Modulus is the scaling or de-scaling factor of transformer. It is represented by ‘TF’ in bond graph representation. Transformer can be easily understood by considering an example in Figure 1.20. An ideal lever with zero mass is considered for establishing a linear relationship between different power variables the lever is assumed to be rigid. Figure 1.21 represents the transformer in bond graph language, where,  $\mu$  is the modulus and the arrow’s direction represents the way modulus is used [4]. Here, ‘e’ represents, ‘f’ represents flow and  $a, b$  are the lengths of the lever from hinged points.

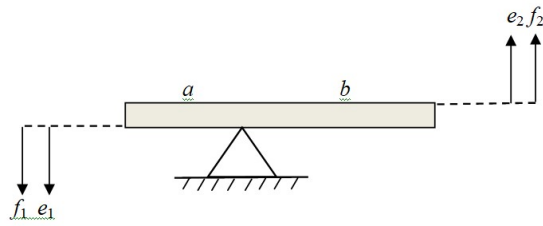


Figure 1.20 Pictorial representation of transformer



Figure 1.21 Depiction of transformer element in bond graph lexicon

$$f_2 = \mu \cdot f_1 \quad (1.8)$$

$$e_2 \cdot \mu = e_1 \quad (1.9)$$

$$e_2 \cdot f_2 = e_1 \cdot f_1 \quad (1.10)$$

Equation 1.8, 1.9 and 1.10 suggest that transformer can convert flow to scale up flow or can de-scale the flow but it cannot convert flow into effort and same is the case for effort.

- Gyrator: Gyrator helps in converting flow ( $f$ ) to effort ( $e$ ) and vice versa. In electrical domain DC motor and in mechanical system mechanical gyroscope represents gyrator shown in Figure 1.22. It is represented by GY in bond graph language. For working of gyroscope, force acting in vertical direction creates another motion in horizontal direction and to maintain motion in vertical direction, a force in horizontal direction is needed. Here,  $\omega$  represents the angular velocity of gyroscope wheel. Figure 1.23 represents gyrator element in bond graph language [4].

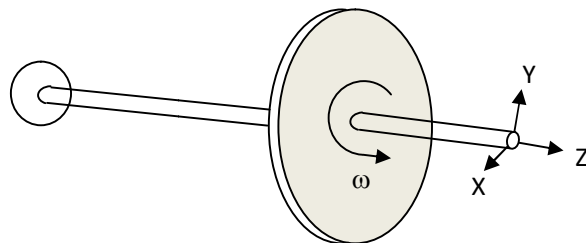


Figure 1.22 Pictorial representation of gyrator

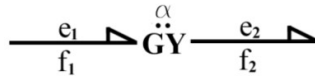


Figure 1.23 Depiction of gyrator element in Bond graph lexicon

$$e_2 = \alpha \cdot f_1 \quad (1.11)$$

$$e_1 = \alpha \cdot f_2 \quad (1.12)$$

$$e_2 \cdot f_2 = e_1 \cdot f_1 \quad (1.13)$$

Equation 1.11, 1.12 and 1.13 suggests that gyrator converts effort to flow and vice versa.

### 1.3.3 Junction elements

There are two types of junction in bond graph language, 0 junction and 1 junction. Any number of bonds can get connected with these junctions as they distribute flow and effort to the whole system.

- Zero junctions: At zero junctions the flow that leaves the junction is equal to the sum of the flow ( $f$ ) entering the junction through various bonds. Here, half arrow direction determines the sign of the flow. For example distribution point of hydraulic pressure.

$$e_1 = e_2 = e_3 = e_4 \quad (1.14)$$

$$f_1 = f_2 + f_3 + f_4 \quad (1.15)$$

$$e_1 \cdot f_1 = e_2 \cdot f_2 + e_3 \cdot f_3 + e_4 \cdot f_4 \quad (1.16)$$

Equation 1.14, 1.15 and 1.16 suggests that at zero junction effort ( $e$ ) remain same and represent summation rule of flow ( $f$ ).

- One junction: One junction is similar to the mesh law. The sum of total efforts at a junction is equal to zero. Flows are represented by half arrows. For example in mechanical system one junction represents common mass point.

$$f_1 = f_2 = f_3 = f_4 \quad (1.17)$$

$$e_1 = e_2 + e_3 + e_4 \quad (1.18)$$

$$e_1 \cdot f_1 = e_2 \cdot f_2 + e_3 \cdot f_3 + e_4 \cdot f_4 \quad (1.19)$$

Equation 1.17, 1.18 and 1.19 suggests that at one junction flow ( $f$ ) remain same and represent summation rule of effort ( $e$ ).

## 1.4 CONTRIBUTION OF THESIS

The hygro-mechanical analysis of composite materials with glass fibre is studied using FEM and bond graph technique. FEM based code is used in Abaqus to perform this analysis. Three-dimensional models have been done using bond graph tools for the verification of the results obtained from Abaqus model. A significant attempt is made to consider all the factors that affect moisture absorption and the resultant stresses that get induced due to moisture ingress. Specimens of three-dimensional models have been fabricated to verify the results obtained from simulation work using a particular experimental set up. The significant contributions of the present thesis work are mentioned below:

- The current study discusses the design and fabrication of composite materials with better resistance towards hot and humid environmental conditions.
- Different fibre orientations have been studied and results have helped in finding out the best possible fibre orientation that can resist moisture absorption in composites.
- Analyses of the stress developed due to moisture ingress under different displacement boundary conditions would help in predicting composite material behaviour under different loading conditions.

## 1.5 THESIS ORGANIZATION

Chapter 1 consists of introduction of composite materials. It includes definition of composites, their types, factors effecting their properties, potential applications *etc.* In later half of this Chapter, introduction to bond graph tool is discussed and different bond graph elements, their uses and physical representation of bond graph tools are explained.

Chapter 2 gives literature study of the whole thesis work. Extensive study of composite materials is done. It mainly includes three areas: (i) Effect of hot and humid environment on composite materials (ii) Effect of use of different types of fibres on the mechanical strength of composite materials (iii) Effect of fibre orientations on the properties of composite materials.

Chapter 3 includes modelling of three-dimensional fibre matrix composites and effect of fibre orientations on the properties of composites. It includes FE code based analysis using Abaqus software. This study is done to find out the best fibre orientation so that moisture ingress can be delayed. Later in this chapter, stresses induced due to moisture absorption in

composite materials are studied. Stresses are calculated and analysed and fibre orientation with minimum stress is obtained.

Chapter 4 contains bond graph approach other than FEM to calculate mass gain and verify the mass gain profiles plotted in Chapter 3. Bond graph tool is used to model three-dimensional models using bond graph elements. As stresses induced are subjected to the displacement boundary conditions, plane strain displacement boundary conditions are used and induced stresses are calculated and analysed.

Chapter 5 includes the experimental work where experimental tests are undertaken to verify the moisture absorption results obtained in Chapter 3. Specimens of three-dimensional models used in Chapter 3 are fabricated to carry out the accelerated moisture diffusion cycles.



## CHAPTER 2

### LITERATURE REVIEW

---

Due to several advantages of FRPs, the research is being extended for applications in aerospace, construction, packaging and automotive industries [5–7]. Besides being light weight, mechanically tough and corrosion resistant, the emphasis is to develop composite materials to improve their effectiveness under weather conditions like hot-humid environments [8, 9]. After fabrication, composite structures operate in a variety of thermal and moisture environments that may have a pronounced effect on their performance. The hygral effects are a result of moisture content variations and are related to difference in hygric properties of constituents. The environmental ageing due to moisture absorption leads to plasticizing, swelling, hydrolysis, oxidation, interfacial de-cohesion [10–12].

The environmental effects can be viewed and analysed from the microscopic point of view, on a scale of fibre diameter, or from the macroscopic point of view, by considering the overall effects on a lamina, which is treated as a homogeneous material. From microscopic viewpoint, fibre architecture is an important aspect that can influence the moisture diffusion. Therefore, there is a need to accurately model the ingress of moisture into composites [13–15]. As the fibre diameter is fairly small in comparison to its length therefore, most of the researches have been conducted using 2-dimensional models. The two dimensional models seem to be a good assumption considering the moisture diffusion across the fibres [16–19]. However, from the diffusion standpoint, it is found that three-dimensional Fickian diffusion phenomenon is a more reliable method to validate the experimental data. It is because the diffusion along the fibres is slightly higher than in the unreinforced resin [13, 20].

The earlier researches conducted using two dimensional fibre matrix architectures have confirmed the effect of fibre matrix architecture on the moisture diffusion [20–22]. In this paper, several three dimensional models with different ply orientations have been investigated. Effect of different fibre orientations on moisture diffusion and resulting stress is determined for the similar moisture boundary conditions. Moisture diffusion also leads to expansion of matrix leading to the development of interfacial stresses. Von Mises stresses and stresses along fibre direction are validated using the concentric cylinder assemblage approach. As an outcome, most suitable fibre matrix models with different fibre orientations have been identified for lower moisture diffusion rates and better stress behaviour.

## 2.1 EFFECT OF MOISTURE AND TEMPERATURE ON COMPOSITE MATERIALS

Composite materials have large advantages in comparison to traditional materials. One of the significant reason behind the use of composite materials is that their properties can be easily controlled according to the requirements. The emphasis is laid to develop composite materials to improve their effectiveness under weather conditions like hot-humid environments [23–25].

To check the composite materials efficiency in hot and humid environment both the effect of temperature and moisture has to be analysed. Recent researchers have worked a lot in this field and have even succeeded in many aspects till now. Moisture absorption in composite materials takes place due to the presence of functional groups that are highly polar in nature. Figure 2.1 represents phases of composite materials where, one phase has more fibre content and other has low fibre content.

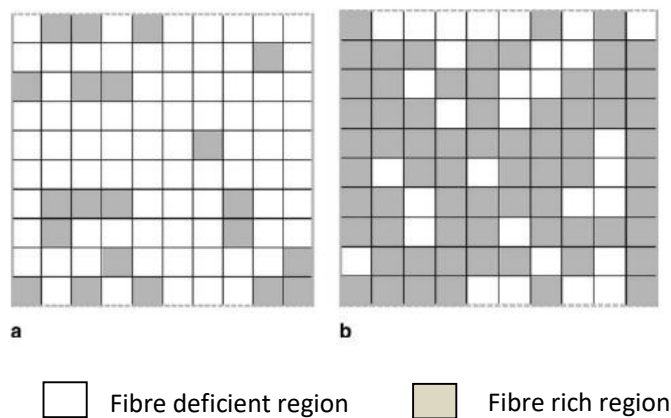


Figure 2.1 Different phases of composite materials [24]

These highly polar functional groups attract water to a large extent. Drawbacks of this absorption are the plasticization and swelling of the composite structures leading to decline of the glass transition temperature of composite materials to the limit at which the composite materials no longer remain stable. So relationship between these two factors is much of concern [26, 27]. Composite materials mainly are made up of fibres and matrix materials where fibres are the reinforcing materials. Many researchers have suggested different ways to distribute fibres among the composite materials and it is found that high stresses are developed in the places where there is high fibre concentration [28]. Mechanical and acoustics response has been also calculated for composite materials with multiple layers of fibres at 60° C at different humid conditions and later fibres were orientated and their effect on moisture diffusion is calculated. Moisture diffusion was found to put significant decrease

on the shear stress and shear modulus and even on acoustic emission as the moisture content increases in the composite materials [29]. While talking about moisture diffusion in composite materials the inter phase region of fibre and matrix becomes a region of great importance where many researchers are focused on. Figure 2.2 shows the entry of moisture into the composite materials when exposed to hot and humid environmental conditions.

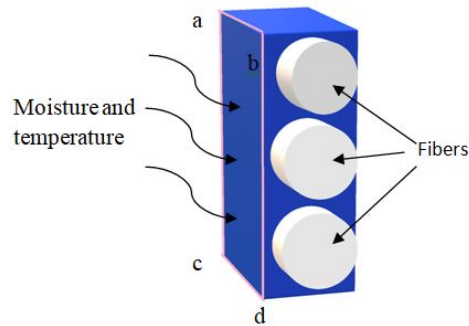


Figure 2.2 face abcd is exposed to moisture and temperature. Hydrothermal process taking place [30]

It has been found that the region that is just few micrometers around the filament is the most effected region in composite on moisture ingress. It has been found by many researchers that there is higher molecular mobility in this region in comparison to the region with bulk resin and this has been found by using Fickian laws using finite element analysis. Stresses are also found to be greater in this region in comparison to other regions [31]. Tortuosity is defined as the ratio of convoluted pathways to the straight line distance between two points. Tortuosity effect has been checked along transverse direction by carefully keeping the spatial arrangement of the fibres that influence inter-filament distance, their angles and size of neighbourhood. Effect of inner fibre distance is calculated and it was found to be really significant. Angle orientations of fibre along with their size also put a significant effect on the moisture diffusion analysis. Many researchers have found that the size of the neighbourhood of the fibres is also of great effect on moisture ingress [32].

## 2.2 TYPES OF FIBRES USED IN COMPOSITE MATERIALS

Researches in composite materials is at high rate but after so much research even this research has turned into another way and later emphasis is laid on the development of composites that are natural or composite should be biodegradable in nature. It is true that from natural composites complete flexibility cannot be reached as the flexibility we have with non biodegradable composites but optimisation is still needed to create green

composites so that they don't harm our nature after they have completed their lifetime. Researchers investigated that the moisture ingress for pineapple-leaf fibre reinforced low density polyethylene (LDPE) composites with different fibre content found to be increasing linearly as the natural fibre content increases [33]. Researchers found that wood flour-polypropylene (PP) composites inhibits moisture diffusion as their concentration increases in the composite materials and this happened due to the encapsulation of wood flour [34].

It has been found that different types of fibres have their different advantages. It has been studied that cotton fibres not only act as reinforcement material but they also act as agents that have microbial abilities. Cotton fibres absorbs reasonable amount of wastes that gets excreted from the wounds therefore, this is the reason that cotton is used for surgical purposes. After studies it has been found that when cotton fibres soaked in the aqueous solution of monomer polymer good mechanical strength can be obtained [31].

Another concept has been developed that is of using hybrid fibres with different combination of natural and synthetic fibres have been developed to meet required properties. Combination of natural fibres with synthetic fibres in cross woven form provides high tensile and impact strength, but when they are modelled unidirectional composites has been found to have more flexural strength when natural fibre Kenaf kept in combination with the synthetic fibres [32].

Another combination developed is the combination of five fibres, three of them are hooked metallic steel, zinc-coated and brass coated and two plastic corrugated polypropylene and hooked polyethylene terephthalate (PET) fibres. And in this combination high flexural is found if high amount of CaO based expansive agent is used and other with zinc or brass coated fibres. High strength is obtained because of formation of calcium hydroxide zinc ate [33]. Figure 2.3 shows different types of fibres used in manufacturing of composites according to their function ability.

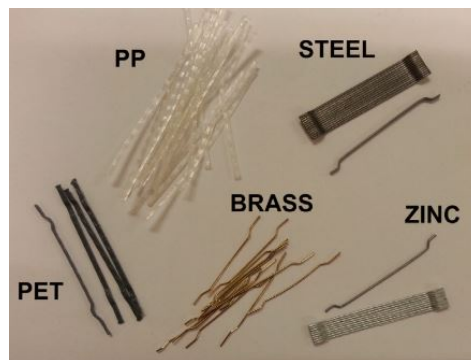


Figure 2.3 Different types of fibres used [33]

Combination of coir and jute fibres is also another good option to make hybridisation. Researchers have found that both increase in dimensional stability and mechanical properties of the ht composite materials. Here, two methods of hybridisation of fibres are considered one is jute / coir / jute or coir /jute / coir. And from these two orientations, jute / coir / jute showed better properties as researchers found that jute act as barrier to moisture ingress and this combination even helps in gaining the desired composite properties [34]. Figure 2.4 represents hybrid composites fibre matrix layups.

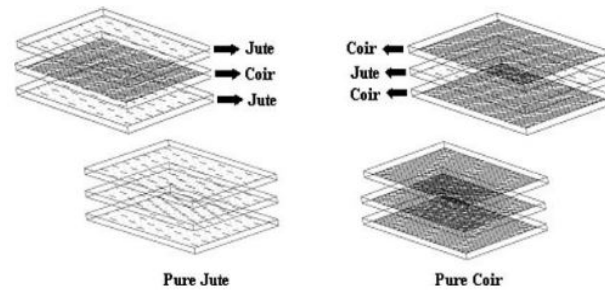


Figure 2.4 Different configuration of jute, coir hybrid composites [34]

### 2.3 DIFFERENT FIBRES ORIENTATION USED IN COMPOSITE MATERIALS

Fibre orientations play a great role in affecting the properties of the composite materials. In the recent researches in the field of composite materials it has been completely found out that fibre orientations put a great effect on the moisture diffusion process in the composite materials and even on the stress induced. It has been found that the time taken by the composite materials to get saturated with moisture and the stresses that get developed due to moisture diffusion into the composite materials can be easily controlled by the fibre direction.

Researchers found that not only the fibre orientation, woven form of fibres also put a significant effect on the composite materials properties and their behaviour in different moisture and stress conditions. Different methods of woven fibres have been discussed as woven fibres just means joining different parts of fibres to make a complete whole just by crossing one fibre over the other. Differently woven techniques including plain, 4, 5 and 8-harness satin and twill, are considered. The authors have tried to find out the net diffusivity of different fibre forms and it has been found out woven composite exhibit faster moisture diffusion than that with composite materials having unidirectional fibre composites.

Different orientations have been discussed by the authors one of them is the warp and weft directions of the fibres with the help of Fick's law the moisture ingress in the composite materials with fibres in warp and weft directions is studied along with stress developed in them are also studied. Warp and weft is the concept of turning fibres into fabrics. In this method warp fibres are kept longitudinally with same tension and along with them transverse weft direction is drawn inserted over and under the warp under different moisture concentration and keeping the temperature constant the study concluded that more is the moisture concentration more is the decline of the tensile strength [9]. Different researchers not only discuss about only fibre orientation but even the fibre clustering in composite materials and the significant spacing between them plays a big role in deciding their behaviour in different moisture conditions and stress conditions. The region around the fibres in the micrometers distance from the fibres is called a region of inter phase and this region is the main deciding factor in finding out the properties of the composite material [18]. Many researchers have also found out that the effective diffusivity of the composite materials depends not only on the distance between two fibres but it also depends upon the relative angular position of the fibre in comparison to other. It is suggested that as the angle between two fibres lies between 0 to 90 degrees it decrease the diffusivity and if it lies between more than 90 degrees it increases the effective diffusivity [11]. Aspect ratio thickness of fibres and fibre orientation are one of the key factors that will affect the moisture diffusion in composite materials. Mass gain in flax acrylic composite is found to be less in comparison to the flax epoxy composite .reasons found are large extent of porosity and the salt molecules decrease the mass diffusion rate and even mass gain content. Along with these all factors that affect moisture ingress, another one of the most significant factor that effect the effective diffusivity is the relative volume fraction of the fibres in comparison to the whole matrix materials.

When analysed for fibre orientation it was found that in flax epoxy composite specimens having fibre orientated in the 45 degree leads to more mass gain in comparison to the specimens having fibres non oriented. Same effect of fibre orientation was found in the flax acrylic composite materials [19]. Figure 2.5 shows cross ply composites where fibres are placed in different layers are perpendicular to each other.

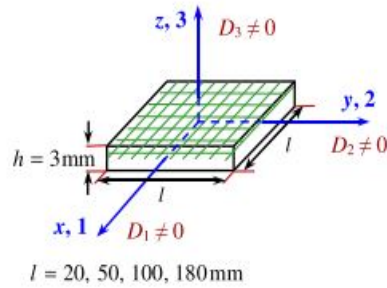


Figure 2.5 Warp and weft fibres orientation [19]

Studies suggest that fibre orientation is less sensitive in comparison to the neighbourhood effect. It has been found that neighbourhood radius of 3 R is enough to develop stresses and if the radius decreases from 3 R then stress concentration increases drastically and for fibre orientation studies concluded that fibres tilted between  $60^\circ$  to  $120^\circ$  yield same stresses [20]. Figure 2.6 shows the effect of fibre neighbourhood on the overall characteristics of composites.

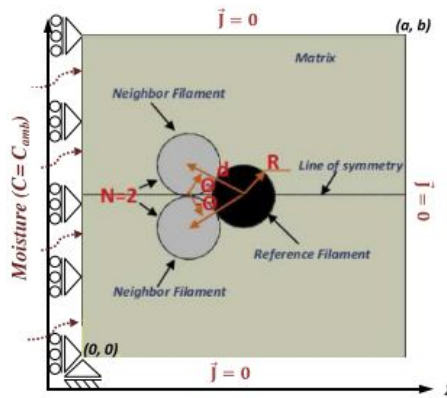


Figure 2.6 Fibres at different angle from the reference fibre [21]

Effect of fibre cluster is also a matter of concern and many researchers have worked on them and have found that spatial clusters of fibre effect moisture ingress and there spatial arrangement can significantly affect the properties of the composite materials. Different types of microstructure are studied. And it is tried to find out the best microstructures which can provide maximum strength and can delay the moisture diffusion to the maximum extent [21–22]. Figure 2.7 represents two types of fibre arrangement methods.

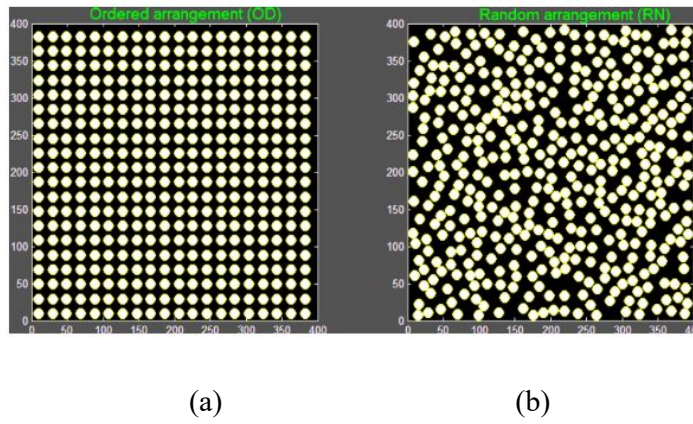


Figure 2.7 (a) Fibre distributed in order and (b) fibres distributed randomly [35]

A sandwich model is also suggested so that all the drawbacks of the composite materials can be removed. In this model between two layers of flax fibres on layer of glass fibre is kept and due to this a significant change in moisture is noticed as glass fibres are hydrophobic in nature and their presence delays the moisture concentration in the composites [23]. Figure 2.8 shows three layer fibre matrix composite with middle layer having different types of fibres.

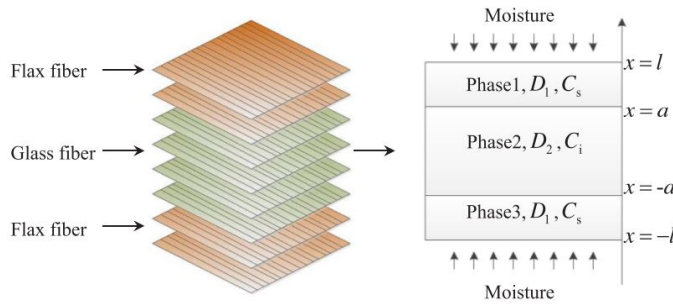


Figure 2.8 Sandwich model of flax/glass/fibre laminates [36]

## 2.4 OBSERVATIONS FROM LITERATURE

After the extensive literature survey from different books and research papers, it has been observed that different types of experimental and analytical studies have been done to predict fibre matrix composites behaviour under hot and humid environment conditions. Under the analytical study it was found that mainly two dimensional fibre matrix models are considered for the analytical study. Researchers have also considered different types of fibres and resins for experimental and simulation work .but there are still some aspects of research that are not considered or are considered very minutely.

- People have worked very less on experimental and analytical study of moisture diffusion on three-dimensional layered fibre matrix composite structures according to Fick's law by orienting fibre into different directions.
- Very few literature is available on experimental and analytical study of stresses produced in the three-dimensional matrix with the moisture ingress has not done yet.
- As per knowledge of the author, modelling three-dimensional models using bond graph theory has not been done yet.

## **2.5 OBJECTIVES OF THESIS WORK**

After studying it is observed that moisture absorption in fibre matrix composites plays a significant role in degradation of composites. Therefore, the objectives of study are decided in order to decrease moisture absorption and resultant stresses that get developed after moisture absorption.

- To analyze moisture diffusion along three-dimensional models of fibre matrix composites with different fibre orientations using FE code Abaqus based on Fick's law
- To analyze the role of different fibre orientation towards the moisture ingress and resulting mechanical stresses
- To perform the hygro-mechanical Stress analysis
- To perform the experimental mass gain studies in controlled environmental conditions
- To model the moisture ingress using the bond graph theory
- To validate the experimental results with the results from FEA and bond graph



## CHAPTER 3

### HYGRO-MECHANICAL ANALYSIS USING FINITE ELEMENT METHOD

In recent times, the composite materials are used for various applications, so there was always a demand to built composite structures that have more strength, toughness and are resistant to hot and humid environmental conditions. Development in the field of composites has a bigger scope as the properties of the composite materials can be changed according to the requirements. The reported study has laid emphasis on the effect of different fibre orientations that can help in improving the durability of composite structures.

#### 3.1 THREE DIMENSIONAL MODELLING

Three-dimensional models of matrix reinforced with fibres along different orientations have been prepared to analyse concentration dependent moisture diffusion inside multidirectional composites. The stress analysis is conducted subsequently. The objective of this work is to predict the moisture diffusion behaviour both along and across the fibres.

##### 3.1.1 Models, Geometry and Boundary Conditions

Initially, four different representative models of unidirectional and cross-ply orientations viz. 0/0/0, 0/90/0, 90/0/90 and 90/90/90 are chosen. Here 0/0/0 and 90/90/90 are unidirectional orientations. The orientation of these models with respect to the direction of moisture diffusion is illustrated in Figure 3.1. The origin is located at point O and the moisture is applied on the YZ-plane ( $x=0$ ). The moisture exposed face is kept same throughout this analysis. In 0/0/0 orientation, fibres in all the three layers are oriented along the direction of moisture diffusion whereas in 90/90/90 orientation, fibres in all the three layers are oriented across the direction of moisture diffusion. For 0/90/0 and 90/0/90 orientations, fibres in the top and bottom layers are placed along and across the direction of moisture diffusion, respectively.

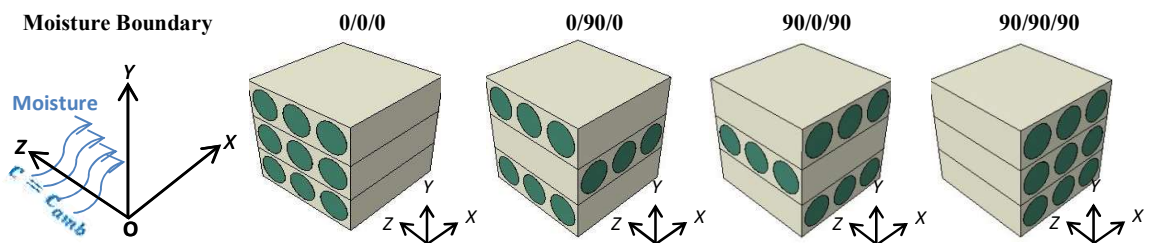


Figure 3.1 Moisture exposed plane for three-dimensional different fibre orientations models

The fibre volume fraction ( $V_f$ ) is approximately 0.5 and this is consistent across all the models. The fibre diameter is assumed to be 22  $\mu\text{m}$ . All the cubic models have same dimensions where ‘a’ is the length of side of cubic model ( $a \times a \times a = 81\mu\text{m} \times 81\mu\text{m} \times 81\mu\text{m}$ ).

The elastic and hygral properties of fibre and matrix are taken from experimental work [10] and these are presented in Table 3.1.

Table 3.1 Fibre and matrix material properties [10]

Property	Fibre	Matrix
Modulus of Elasticity ( $E$ )	70 GPa	2.7 GPa
Poisson's Ratio ( $\nu$ )	0.35	0.35
Mass density ( $\rho$ )	1780 $\text{kg/m}^3$	1150 $\text{kg/m}^3$
Diffusivity ( $D_m$ )	0	$15 \times 10^{-13} \text{ m}^2/\text{s}$
Moisture expansion coefficient ( $\beta_h$ )	0	$10^{-3}$ per % of $\text{H}_2\text{O}$

The boundary conditions are considered as follows:

(a) *Boundary Condition (Moisture)*

Initially, the composite is assumed to be in dry condition. Hence, initial moisture concentration is zero (Equation 3.1). As soon as the composite is subjected to environmental moisture, the left surface along a  $YZ$ -plane ( $X=0$ ) is subjected to the ambient moisture concentration ( $C_{\text{amb}}$ ). This boundary condition is illustrated in Figure 3.1 and is presented by Equation 3.2. The moisture gradient results in the mass transport from moisture exposed to the moisture deficient planes till the whole volume attains the moisture concentration of  $C_{\text{amb}}$ .

$$C = 0 \quad (0 \leq x \leq a, \forall t = 0) \quad (3.1)$$

$$C = C_{\text{amb}} \quad (x = 0, \forall t > 0) \quad (3.2)$$

(b) *Boundary Condition (Mass flux)*

No mass flux ( $\vec{J}$ ) is allowed to either enter or leave the rest of the five planes throughout the analysis i.e.

$$\vec{J} = 0 \quad (y = 0, y = a, z = 0, z = a, x = a, \forall t \geq 0) \quad (3.3)$$

### 3.1.2 Moisture Diffusion Analysis

In this section moisture absorption in composites is studied using Fick's law. For carrying out the analysis using Fick's law, following are the assumptions that are to be taken in order to meet the conditions of Fick's law:

- Moisture diffusion occurs only through matrix phase, no absorption of moisture is considered in fibre phase.
- No chemical reaction takes place between the absorbed moisture and the composite material.
- Value of diffusivity does not change with entry of moisture in composites and it is independent of temperature and other environmental factors.

Under these assumptions, the composite models can be analysed based on simple Fick's law. The governing equations for finite element calculations are the extensions of Fick's first law. Further, Fick's second law provides a fundamental relation between dimensions of the diffusion domain and time elapsed through its three-dimensional form as follows:

$$\frac{\partial c}{\partial t} = D_m \left( \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \quad (3.4)$$

Where,  $c$  is the boundary moisture-content and  $D_m$  is the material diffusivity. The concentration gradients along three orthogonal directions are expressed as  $\partial c/\partial x$ ,  $\partial c/\partial y$  and  $\partial c/\partial z$ , respectively. The concentration gradient leads to moisture diffusion. The simplification through these assumptions ensures linear mass transport behaviour and helps to identify the effects of several other parameters. Once the behaviour is understood, these assumptions can be relaxed for a practical system. Considering the aforementioned assumptions, Fick's law can be written as

$$\frac{c(t) - c_i}{c_{amb} - c_i} = 1 - \frac{64}{\pi^3} \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{(-1)^i (-1)^j (-1)^k}{(2i+1)(2j+1)(2k+1)} \times \cos \frac{(2i+1)\pi x}{a} \cos \frac{(2j+1)\pi y}{b} \cos \frac{(2k+1)\pi z}{c} e^{\left[ -\pi^2 t D_m \left( \left( \frac{2i+1}{a} \right)^2 + \left( \frac{2j+1}{b} \right)^2 + \left( \frac{2k+1}{c} \right)^2 \right) \right]} \quad (3.5)$$

Where  $c_i, c_{amb}$  and  $c(t)$  are the initial concentration, ambient concentration and concentration at time ( $t$ ), respectively.  $a, b, c$  are the dimensions of 3D-fibre matrix polymer along  $x, y$  and  $z$  directions, respectively. The mass gain due to moisture diffusion can be calculated by integrating Equation (3.5) over volume and time and the fractional increase in mass is calculated as

$$\frac{M_t}{M_\infty} = 1 - \left(\frac{8}{\pi^2}\right)^3 \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{1}{((2i+1)(2j+1)(2k+1))^2} e^{\left[-\pi^2 t D_m \left( \left(\frac{2i+1}{a}\right)^2 + \left(\frac{2j+1}{b}\right)^2 + \left(\frac{2k+1}{c}\right)^2 \right)\right]} \quad (3.6)$$

The moisture diffusion through different fibre matrix architectures is analysed with the help of commercially available Finite Element (FE) code [37] based on Fick's law. The ambient moisture concentration ( $C_{amb}$ ) is chosen as 2%. Moisture concentration is the primary solution variable which is computed at the end of each time step on all the nodes. Meshing is done using 8 node brick (C3D8P) elements. The FE models are heterogeneous with multiple fibres matrix orientations. Figure 3.2 shows a meshed geometry. A prior convergence study was conducted on mesh size. Owing to heterogeneous nature of the models, it requires fine meshing for the closest approximation. A typical model with chosen mesh size contains almost 10,000 elements. As the fibres are non-diffusive, the moisture diffusion occurs only through the matrix.

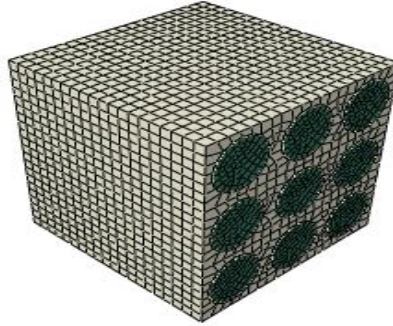


Figure 3.2 Element meshes over the entire domain for a typical model

Therefore, mesh size has to be kept fine in the areas of more consideration. Mesh size in the matrix region plays a significant role as only the matrix allows moisture to flow through it. Mesh element is to be used more precisely as for different analysis to be performed with different types of mesh elements given in the Abaqus software. This is not the matter of qualitative study but it is the matter of quantitative study how accuracy can be controlled using different mesh-type and different mesh element size.

Mesh size is a very significant issue in relation with the accuracy of the finite element models and choosing the correct mesh element type and size can affect the accuracy of the results. On every node, there is mass concentration as the single degree-of-freedom is computed at the end of every step. The minimum step time is calculated by the relation of Equation (3.7) in which  $\Delta l$  represents the mesh edge size,  $D$  represents moisture diffusivity and  $\Delta t$  represents time step size.

$$\Delta t \geq \Delta l^2 / 6D \quad (3.7)$$

### 3.1.3 Results

Figure 3.3 shows the moisture concentration profiles for different orientations along with time. During the initial phase, until time ( $t$ ) is 400s, the moisture progression is almost similar in all the models. Once the moisture encounters the non-diffusive fibres across its path of progression, their orientation proves quite prominent in generating the moisture barrier. 0/0/0 and 90/90/90 orientations can be considered as the topological extremes here in this work. The fibres are non-diffusive and hence, the moisture progresses only through matrix resin. In 90/90/90 orientation, all the fibres are oriented across the direction of the moisture diffusion and this result in a higher resistance to the moisture progression. Therefore, 90/90/90 orientation takes highest time to get saturated as compared to other three orientations. With two and single layer of fibres are laid across the direction of diffusion. 90/0/90 and 0/90/0 are the second and third best orientations, respectively in terms of resistance to the moisture diffusion. At time ( $t$ ) is 6000 s, it can be noticed that when 0/0/0 orientation is saturated with boundary moisture, the other three orientations are saturated partially.

Figure 3.4 shows the relative mass gain  $M_t/M_\infty$  with respect to time. Here,  $M_t$  is instantaneous mass and  $M_\infty$  is the saturated mass of the composite. The mass gain behaviour can be easily described through Equation (3.6) which states that the saturation state is achieved asymptotically. This is the only reason that curves for fractional mass uptake reaches to its limit asymptotically. It can be noticed initially up to 500 s, the mass gain profiles overlap each other and mass diffusion is found to be slightly more in 90/90/90 orientation. This is primarily due to the resin phase that gets saturated before encountering

fibre barrier. This difference in mass gain gets more intensified as soon as the moisture encounters the fibres across its direction of diffusion.

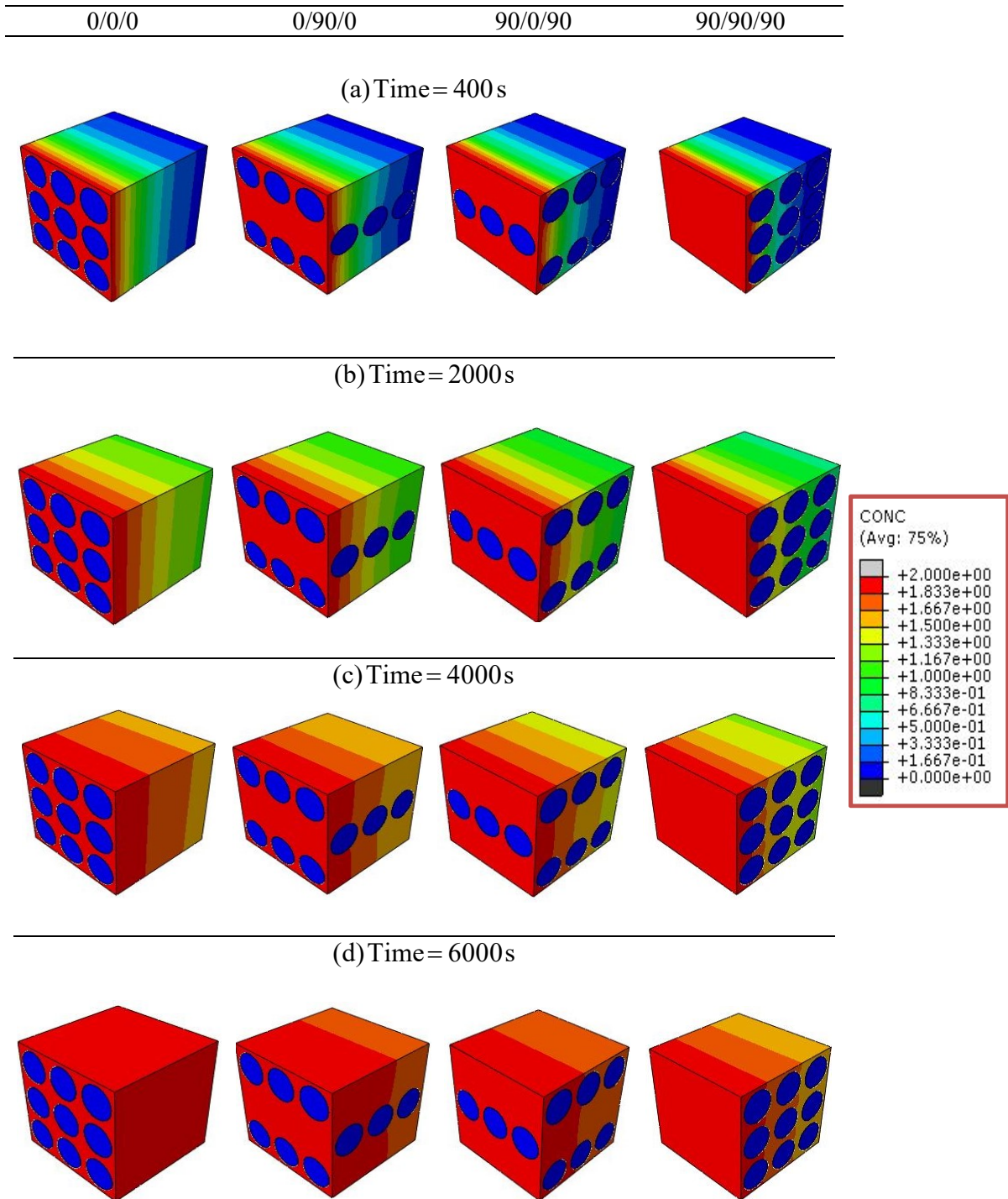


Figure 3.3 Moisture progression at different time instances of (a) 400 s, (b) 2000 s, (c) 4000s and (d) 6000s

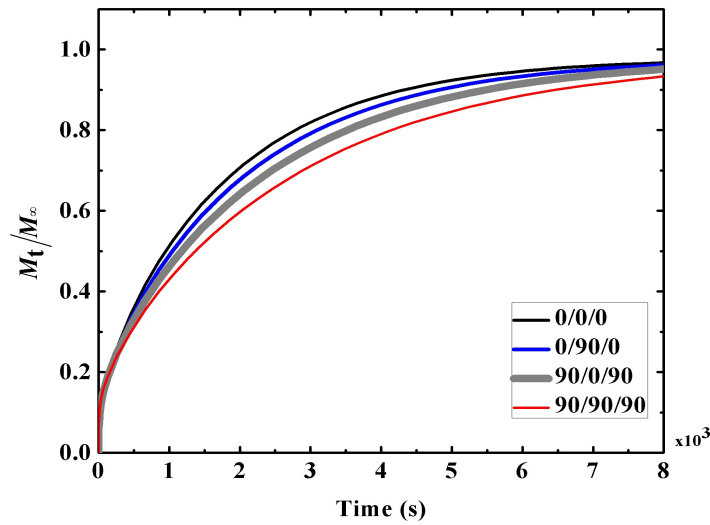


Figure 3.4 Ratio of saturated volume to the total volume for (0/0/0), (0/90/0), (90/0/90) and (90/90/90) orientations

Figure 3.5(a) illustrates the length parameters along the direction of diffusion. The influence of fibre orientation on the rate of saturation can also be understood from Figure 3.5(b). Here,  $x/L$  represents fraction of length saturated length along the direction of moisture diffusion ( $x$ -direction). In Figure 3.5(b), it is seen that initially the curves corresponding to 90/0/90 and 90/90/90 orientation have higher slopes as compared to other lines. This is due to initially faster diffusion rate in these two models. The faster diffusion rate occurs due to the deficiency of non-diffusive fibres along the diffusion path. In these two models, the moisture mainly encounters the matrix initially and this helps in the faster progression of moisture during the initial phase approximately up to 2000 s. Here, the slope of the curve reduces from 2000 s to 6000 s. This is the duration when moisture encounters the fibre barrier across its direction of progression. The across presence of fibres impedes the mass progression which further reduces the rate of saturation along the direction of moisture flow. The rate of length saturation follows the order  $0/0/0 > 0/90/0 > 90/0/90 > 90/90/90$ , and 90/90/90 orientation takes almost 50% more time to be fully saturated as compared to the 0/0/0 orientation.

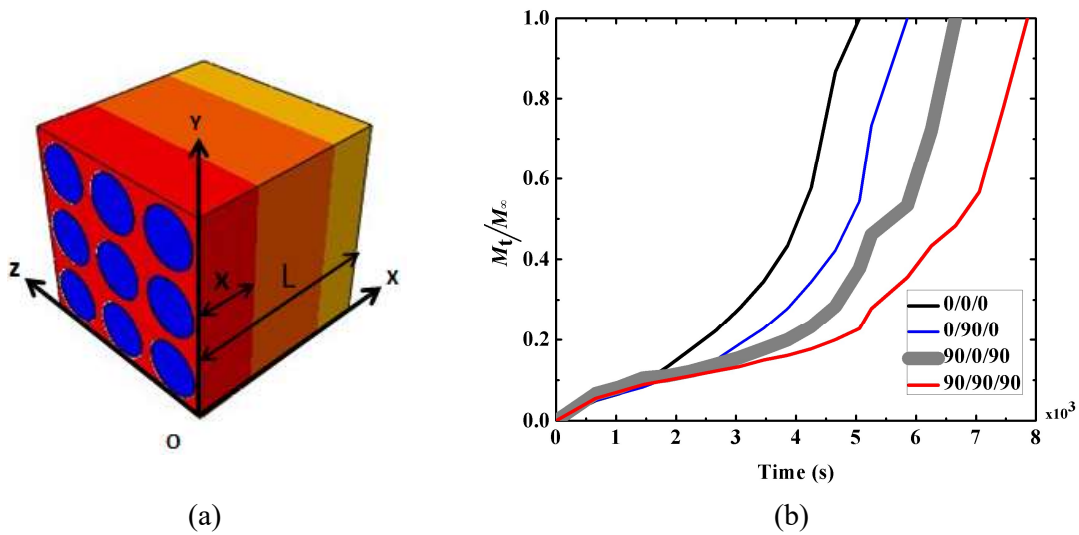


Figure 3.5 (a) Three-dimensional model and (b) variation of saturated length ( $x$ ) to total length graph ( $L$ )

### 3.1.4 Angle Ply Orientations

Two more configurations 0/45/0 and 90/45/90 with angle ply orientation of 45° in the middle layer are analysed (Figure 3.6). The objective is to observe effect of change in the orientation from cross ply to angle ply on the moisture diffusion. The modelling environment viz. dimensions, layer thickness, meshing, and boundary conditions *etc.* are similar to the ones used in previous section while analyzing the cross-ply orientations. Figure 3.7 shows the snapshots of mass concentration profiles. As evident from the colour profiles, 0/45/0 orientation saturates much earlier as compared to 90/45/90 orientation. The barrier effect is notable during the later stages of moisture progression.

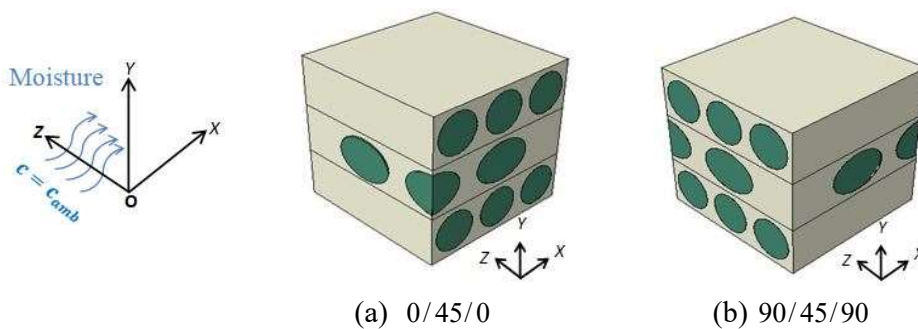


Figure 3.6 Moisture exposed plane for angle ply orientations model

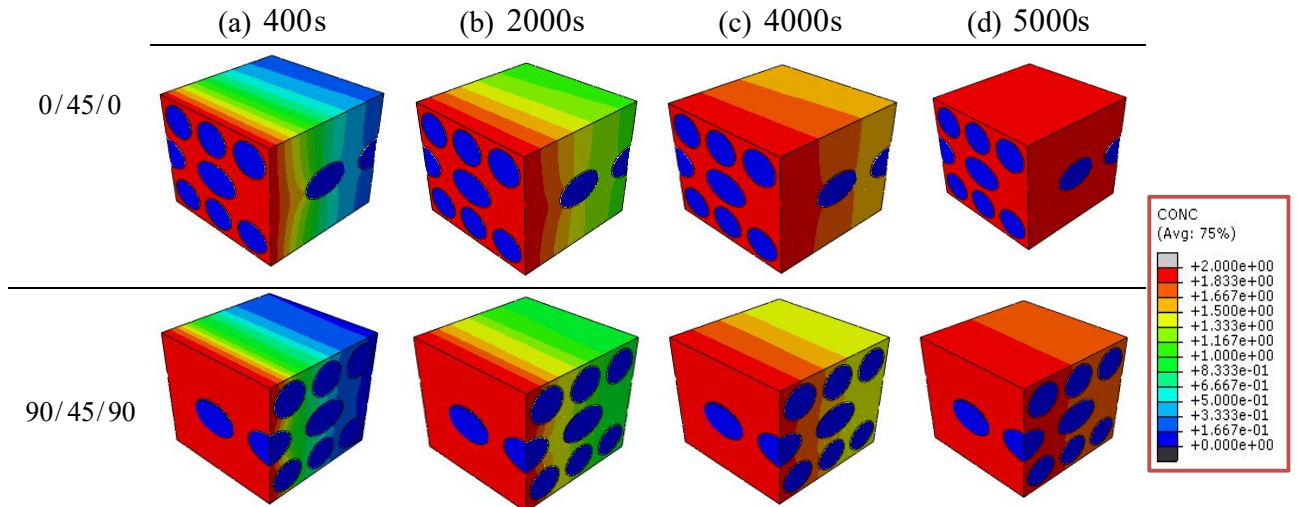


Figure 3.7 Moisture progression at different time instances for (0/45/0), (90/45/90) at (a) 400s, (b) 2000s, (c) 4000s and (d) 5000s

Figure 3.8 shows the relative mass gain curves to envisage the effect of angle ply for (0/0/0 with 0/45/0) and (90/90/90 with 90/45/90) orientation. It is seen comparing the first set of orientations (0/0/0 with 0/45/0) that transformation from 0° to 45° orientation of middle layer has increased the barrier effect marginally and this results in slightly lesser mass gain in 0/45/0 as compared to 0/0/0 orientation. It is observed comparing the second set of orientations (90/90/90 with 90/45/90), that transformation from 0° to 45° orientation of middle layer has reduced the barrier effect marginally and this results in slightly higher mass gain in 90/45/90 as compared to 90/90/90 across all the time instances.

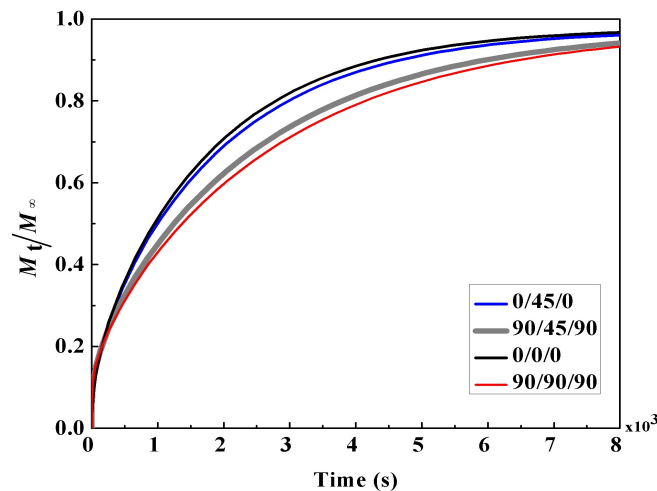


Figure 3.8 Ratio of saturated volume to the total volume for (0/0/0), (0/45/0), (90/45/90) and (90/90/90) orientations

### 3.1.5 Comparisons with Different Empirical Techniques

For the preliminary investigations, the topological extremes i.e. 0/0/0 and 90/90/90 are chosen. The mass gain through these models is compared with respect to mass gain inside the smeared models based on widely used micromechanics theories viz. rule of mixtures [38] and Halpin-Tsai theory [39]. On the basis of rule of mixtures, the effective diffusivity  $D_{\text{eff}}$  of smeared models is calculated as

$$D_{\text{eff}} = V_m D_m + V_f D_f \quad (3.8)$$

On the basis of Halpin-Tsai theory, effective diffusivity is calculated as

$$D_{\text{eff}} = \frac{1 - V_f}{1 + V_f} D_m \quad (3.9)$$

Here,  $V_m$  and  $V_f$  are volume fraction;  $D_m$  and  $D_f$  are the diffusivities of fibre and matrix phase, respectively. Figure 3.8 shows the relative mass gain calculated by integrating the nodal moisture concentration over the entire domain with the progression of moisture. It is clear that models under consideration are in reasonable agreement with the theories of micromechanics.

Figure 3.9 represents the FEM modelling of three-dimensional models allowing moisture diffusion in healthy relation with rule of mixture theory as defined above. The rule of mixture graph lies between the moisture progression graph of 0/0/0 and 90/90/90 orientations.

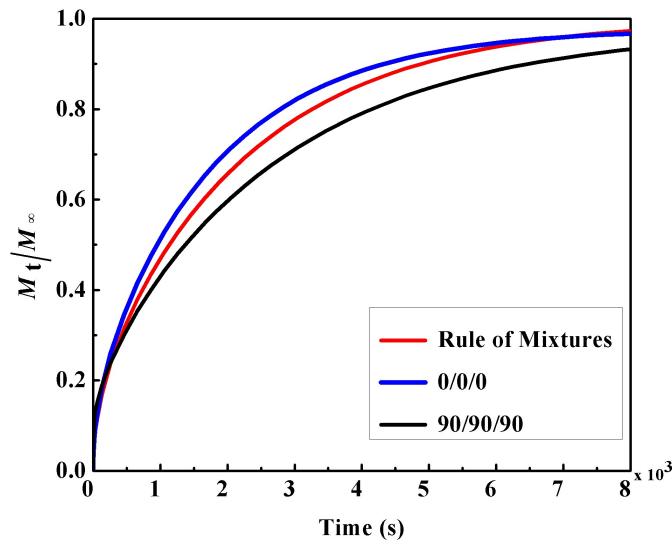


Figure 3.9 Comparison of moisture progression using FEM with rule of mixtures

Figure 3.10 supports the results plotted in Figure 3.8. The Halpin-Tsai mixture theory is in correct relation with the moisture ingress plots of 0/0/0 and 90/90/90 and lies just below the plots of other fibre orientations.

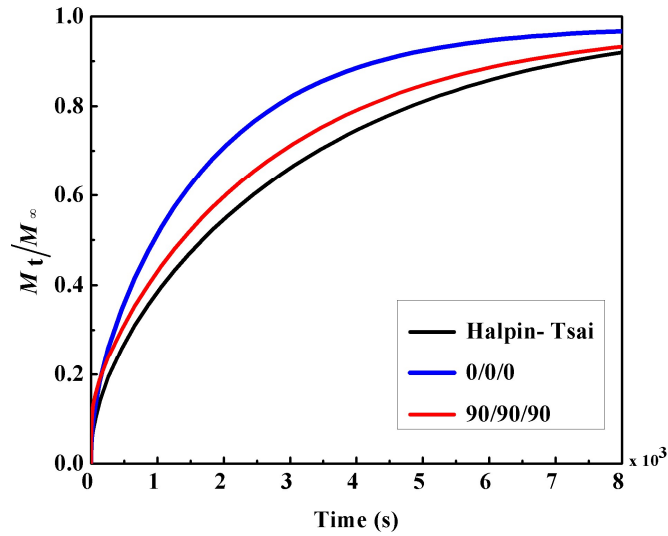


Figure 3.10 Comparison of moisture progression plots with Halpin-Tsai graph

### 3.2 HYGRO-MECHANICAL ANALYSIS

The study of residual stresses is of great importance. The generation of these stresses leads to reduction in mechanical strength, decrease in life span of composite structures. The degradation in composite materials is shown in Figure 3.11.



Figure 3.11 Degradation in composite materials [2]

Under the moisture diffusion conditions, stresses are induced in a composite due to the difference in the expansion of fibre and matrix. In this section, the influence of fibre

orientation on the stress behaviour is investigated. The three-dimensional models investigated in previous section with variable fibre orientations are investigated in this section to observe the stresses induced alongside fibre, matrix and interface with the moisture saturation.

### 3.2.1 Concentric Cylinder Assemblage (CCA) model

The axial stresses are validated using micromechanics based concentric cylinder assemblage (CCA) approach. In this approach, a fibre within matrix is represented as an assemblage of concentric cylinders. Figure 3.12 shows an analogy between present three-dimensional models and concentric cylinder assemblage of multiple fibres. The core of each cylinder is a fibre and surrounding annulus is a matrix material. Fibres are generally cylindrical in nature and the resultant cylinder is called the composite cylinder. The radii of all the fibres as well as of the composite cylinder are not of same. The advantage of this assemblage model is that one fibre matrix cylinder can be used to find out the behaviour of the whole assemblage model where all the fibres are bound together and these are coated with matrix to make a new composite material. As the composite is assumed to be transversely isotropic, the ratio of fibre to matrix volume for the all the composite cylinders is same.

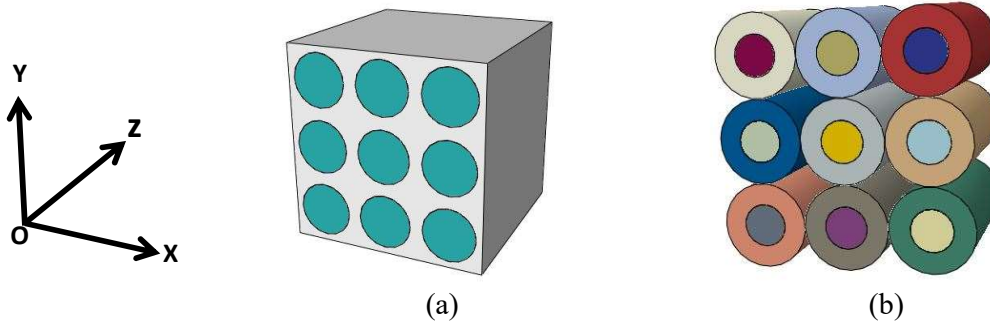


Figure 3.12 (a) Three-dimensional Abaqus model and (b) concentric cylinder assemblage model

Figure 3.13 shows a single concentric cylinder along the polar coordinates. The fibre is unidirectional and matrix is assumed to uniformly surround the fibres. The CCA model uses linear elastic theory for the calculations of stress and strain [40]. The outer surface of surrounding matrix is subjected to concentration gradient which leads to the development of moisture induced stresses. At saturation, concentration is assumed to be uniform throughout the matrix and it is also assumed that model is initially stressed free. For an axi-symmetric CCA model, the equilibrium equations are represented as

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \quad (3.10)$$

The radial, circumferential and axial strains are given by

$$\varepsilon_r = \frac{du}{dr}, \varepsilon_\theta = \frac{u}{r}, \varepsilon_z = \frac{dw}{dz} \quad (3.11)$$

Here,  $u$ ,  $v$  and  $w$  represent displacements along  $x$ ,  $y$  and  $z$  directions, respectively and are independent along these directions.  $u$  is independent of  $z$  as the fibres and matrix cylinders are assumed to be infinitely long. Similarly,  $w$  is independent of  $r$ , otherwise, it violates iso-strain conditions along  $z$ -direction. The resultant compatibility condition is

$$\frac{d\varepsilon_\theta}{dr} + \frac{\varepsilon_\theta - \varepsilon_r}{r} = 0 \quad (3.12)$$

Here, hygral strains act as additional strains and are needed to be subtracted and the corresponding stresses are

$$\sigma_r = \lambda(\varepsilon_r + \varepsilon_\theta + \varepsilon_z - 3\beta_h \Delta C) + 2G(\varepsilon_r - \beta_h \Delta C) \quad (3.13)$$

$$\sigma_\theta = \lambda(\varepsilon_r + \varepsilon_\theta + \varepsilon_z - 3\beta_h \Delta C) + 2G(\varepsilon_\theta - \beta_h \Delta C) \quad (3.14)$$

$$\sigma_z = \lambda(\varepsilon_r + \varepsilon_\theta + \varepsilon_z - 3\beta_h \Delta C) + 2G(\varepsilon_z - \beta_h \Delta C) \quad (3.15)$$

Where,  $\lambda$  Lamé's constant and  $G$  is shear modulus.  $E$ ,  $\lambda$ ,  $G$  and  $\beta_h$  are material specific. The axial stresses in the matrix and fibre when under uniform moisture distribution are

$$\sigma_z^{\text{matrix}} = (\beta_f - \beta_m) \Delta C E_m \left[ \frac{\lambda_1}{\lambda_2} \left[ \frac{E_f}{E_c} \right] \left[ \frac{V_f}{1 - V_m} \right] \right] \quad (3.16)$$

Where , 
$$\lambda_1 = \left( 1 - \frac{1}{2} \left\{ \frac{1 - 2\nu}{1 - \nu} \right\} \left\{ \frac{1 - E_c}{1 - E_f} \right\} \right) \quad \text{and} \quad \lambda_2 = \frac{1}{2} \left[ 1 - \frac{E_c}{E_f} \right]$$

$$\sigma_z^{\text{fibre}} = -\frac{V_m}{V_f} \sigma_z^{\text{matrix}} \quad (3.17)$$

Where,  $E_c$  is the longitudinal Young's modulus of the composite and can be computed using the rule of mixture referring to the volume fraction of individual matrix  $V_m$  and fibre phase  $V_f$ . Subscripts with  $f$  and  $m$  are for fibre and matrix, respectively.

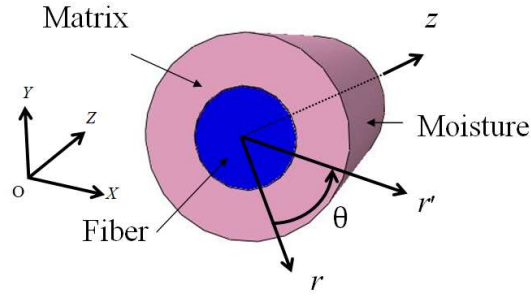


Figure 3.13 Unidirectional fibre matrix composite along the polar coordinates  $(r, \theta, z)$

### 3.2.2 Boundary Conditions

Figure 3.14 illustrates the boundary conditions imposed to analyse the stress behaviour. Figure 3.14(a) shows the moisture boundary conditions applied on top, bottom, left and right planes of 0/90/0 orientation. These can be described as

$$C = C_{amb}(x = 0, x = a, y = 0, y = a, \forall t > 0) \quad (3.18)$$

As no mass flux ( $\vec{J}$ ) is allowed to either enter or leave the front and rear planes throughout the analysis.

$$\vec{J} = 0 \quad (z = 0, z = a, \forall t \geq 0) \quad (3.19)$$

The axial and von Mises stresses are determined along both these planes. 0/90/0, 90/0/90, 90/45/90 and 90/90/90 orientations having same dimensions as used in previous section are analysed. The orientation 0/0/0 is not included. It is due to the absence of load bearing fibre orientations on front and rear planes and the moisture diffusion in this orientation was really fast in comparison to other orientations.

Here, front and back planes are also termed as free planes as the displacement boundary conditions on the adjacent planes results in a controlled expansion of these two planes along the z-axis. Figure 3.14(b<sub>1</sub>, b<sub>2</sub>) illustrates the displacement boundary conditions applied in addition to the moisture boundary conditions. These views are produced rotating the view in Figure 3.14(a) about the axis (A) firstly along counter clock wise (Figure 3.14(b)) and then along the clockwise direction (Figure 3.14(c)) when viewed from top. The displacement boundary conditions presented in both these views can be mutually described by

$$U_1 = 0 \quad (x = 0, a) \quad (3.20)$$

$$U_2 = 0 \quad (y = 0, a) \quad (3.21)$$

Where,  $U_1$  and  $U_2$  are the displacements along  $x$  and  $y$  -axis, respectively. These applied moisture and displacement boundary conditions result in a symmetric expansion of both front and rear planes along the  $z$ -axis.

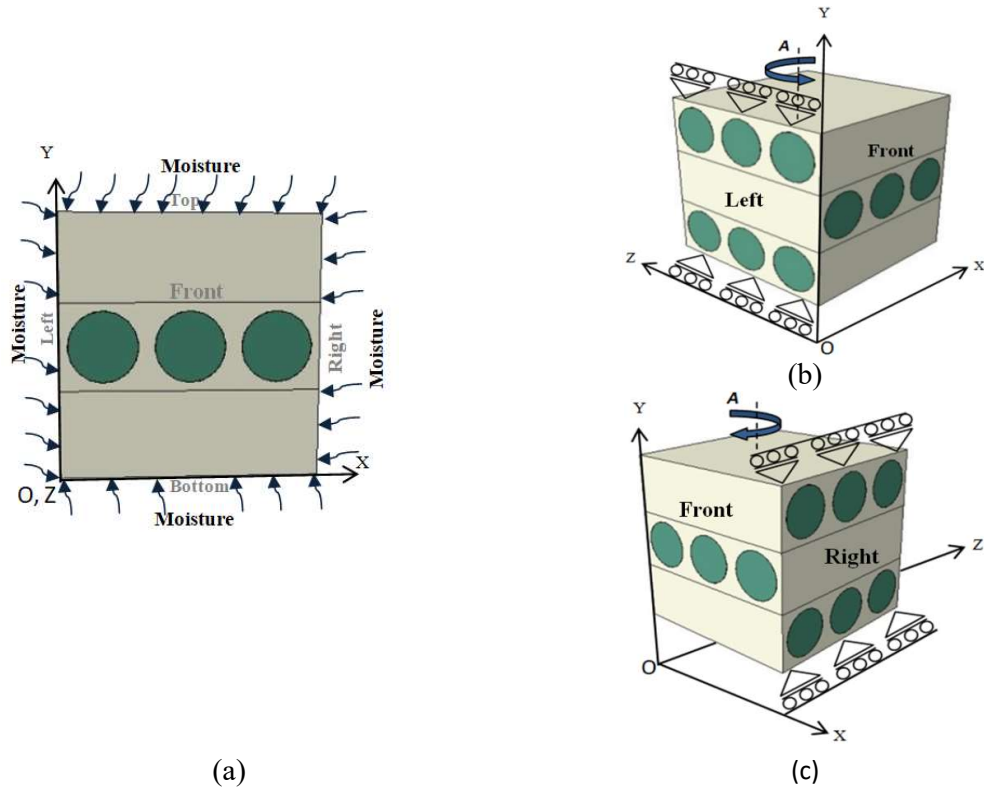


Figure 3.14 Generalised boundary conditions for three-dimensional models (a) front face, (b) left plane and (c) right plane

### 3.2.3 Coupled Diffusion Stress Analysis

Hygro-mechanical stress analysis is conducted using a coupled temperature displacement procedure [19]. Using the analogy between Fourier law of heat conduction and Fickian law of mass diffusion, the moisture diffusivity ( $D$ ) is defined in terms of equivalent thermal diffusivity ( $D_t$ ). This is implemented substituting diffusivity by defining  $D = D_t = k / (\rho c_p)$  where  $k$ ,  $\rho$  and  $c_p$  describes thermal conductivity, mass density and specific heat, respectively. All the models were meshed using displacement and thermally coupled elements C3D8T and CPE4T. Von Mises stresses and longitudinal stresses along fibre length are calculated. As the matrix is free to expand along  $z$ -direction, owing to its higher modulus of elasticity, fibre resists this expansion of matrix. As a resultant, fibre receives a pull along the direction of expansion of matrix which leads to rise in interfacial stresses. Figure 3.15 shows the snapshots of the axial stress  $\sigma_z$  and von Mises stress. For a given model, the axial stress distributions are identical along both the free planes (i.e. front and rear plane). With the progression of moisture, the interfacial stresses develop due to the presence of fibre with

negligible (or zero) coefficient of fibre expansion in comparison to the matrix. It can be noticed that stresses in the vicinity of free planes (front/rear) are higher as compared to the intermediate regions. Further, on the free planes, it is found that the stresses developed on the fibre side interfaces are relatively higher in comparison to the matrix rich planes. The stresses developed on the matrix rich planes are found to be negative representing the compressive stresses developed in the matrices. These results represent the confirmation of the concentric cylinder assemblage theory given in Equation (3.16, 3.17).

### 3.2.4 Results and Comparison with CCA

On a careful observation of von Mises stresses, it can be noticed that stress magnitude is lowest for the fibres which are laid along the moisture exposed planes. The fibres which are laid across the direction of moisture progression endure higher stress magnitudes. In the angle ply configurations (0/45/0 and 90/45/90), the stresses on the free planes are much lower for the fibres that are laid at 45°. This is due to an angular orientation resulting in a stress relaxation for the fibres which are otherwise much stiffer under the tensile loads, but the 0/45/0 orientation is not considered for subsequent study because it has higher rate of moisture progression and in this orientation load carrying fibres are oblique to the free planes where stresses are calculated. Figure 3.16 shows a cut-section view along the middle layer. It illustrates the stresses in the vicinity of fibre on the deformed free plane. The free expansion of epoxy and pull by fibre leads to the stress magnitude that grows rapidly from matrix towards the interface and reaches its peak value at the interface.

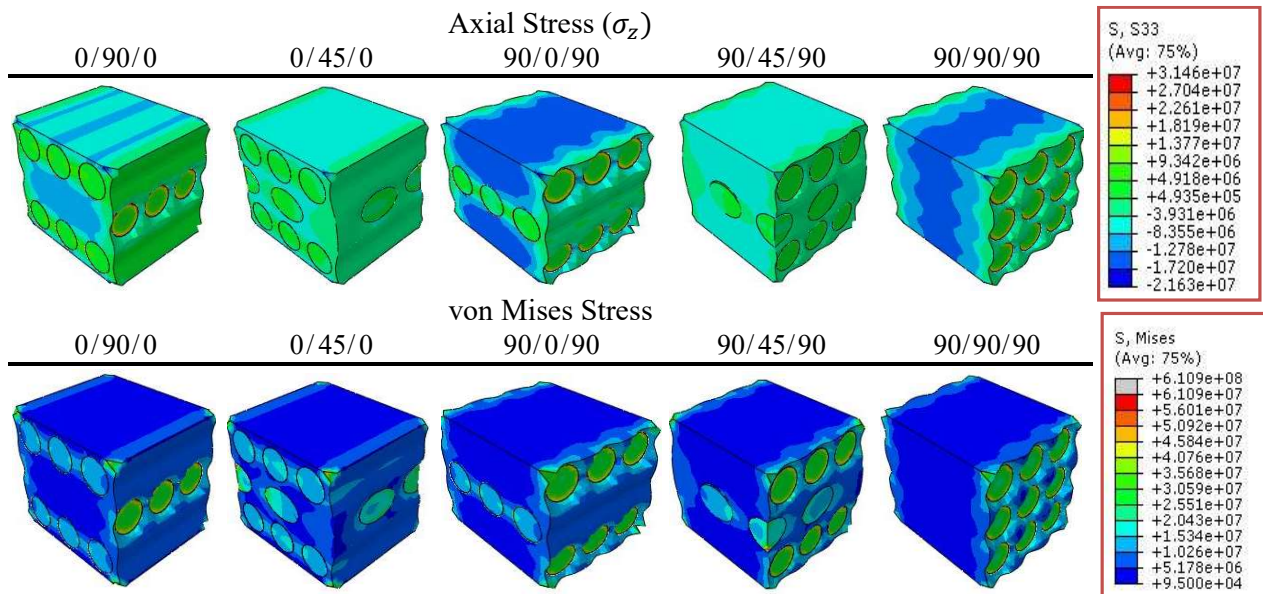


Figure 3.15 Stresses produced on the free face when moisture diffusion reaches its saturation

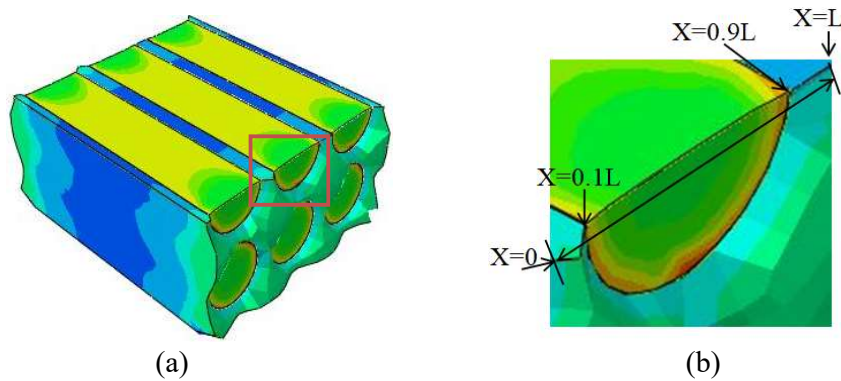


Figure 3.16 (a) Cut section of three-dimensional model and (b) enlarged view of region entrapped in red square

The stresses are measured inside a representative volume element (RVE) alongside a length ( $X/L=0$  to  $1$ ). Figure 3.17 plots variation of axial stress ( $\sigma_z$ ) in the vicinity of fibre. The stress magnitudes are plotted for all the four orientations along  $X$ -direction. Here,  $0 \leq X/L \leq 0.1$  and  $0.9 \leq X/L \leq 1$  represent the matrix region and  $0.1 \leq X/L \leq 0.9$  is indicative of fibre region. Among  $90/90/90$ ,  $90/0/90$  and  $0/90/0$  orientations, the  $90/90/90$  orientation has maximum number of fibres on the free planes which results in a load dispersal among them. Hence, the stress magnitude is least for  $90/90/90$  orientation as compared to the other two. The resultant stresses increase with the reduction of load bearing fibres on the free plane. Therefore,  $90/0/90$  and  $0/90/0$  are the second and third best configurations, respectively.

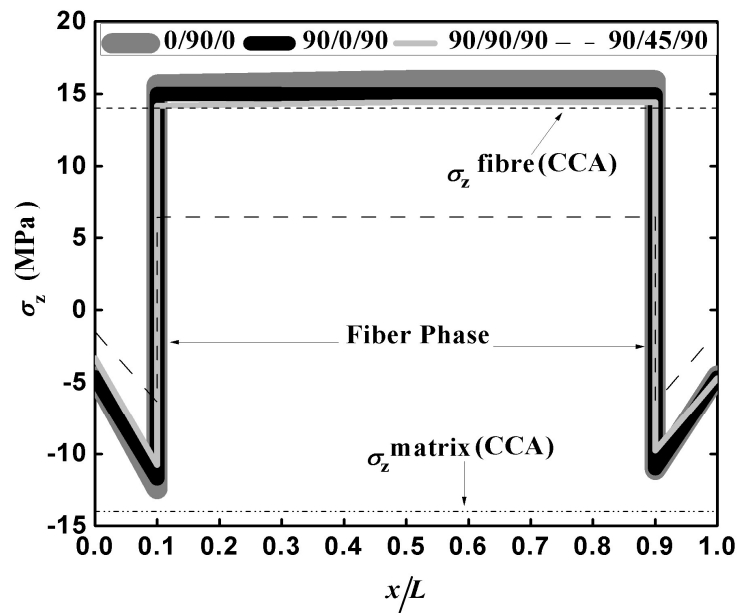


Figure 3.17 Axial stresses ( $\sigma_z$ ) on the free plane along the fibre and matrix zones

For 90/45/90 orientation, the stress magnitude around and inside the fibre oriented at 45° is at lowest. As explained earlier, this is due to the load relaxation owed to its angular inclination. It may be noted that stresses plotted for 90/45/90 is not indicative of axial stress for the fibres present at 90° in top and bottom layers of this configuration.

As the volume fraction of the fibre and matrix is almost similar ( $\approx 0.5$  each), according to the Equation (3.17), the axial stresses developed at the interface ( $X/L=0.1$  and  $0.9$ ) in the fibre region are equal and opposite to the axial stresses developed in the matrix region. The magnitudes at the interface are in close approximation to the ones given by CCA algorithm (Equation (3.15–3.17)). Further, the stresses developed on the matrix side increases in magnitude towards the interface and maximum at the interface due to interfacial cohesion. Figure 3.18 shows the overall stress behaviour accounted by von Mises criterion. The distribution of von Mises is similar to the axial stress especially within matrix and at interface. Within the fibre, the overall stresses reach maximum values at the interface and reduce gradually towards the fibre axis. Ignoring the stresses around fibre in middle layer of 90/45/90 orientation, the overall stresses on the free planes follows the order  $90/90/90 < 90/45/90 < 90/0/90 < 0/90/0$ .

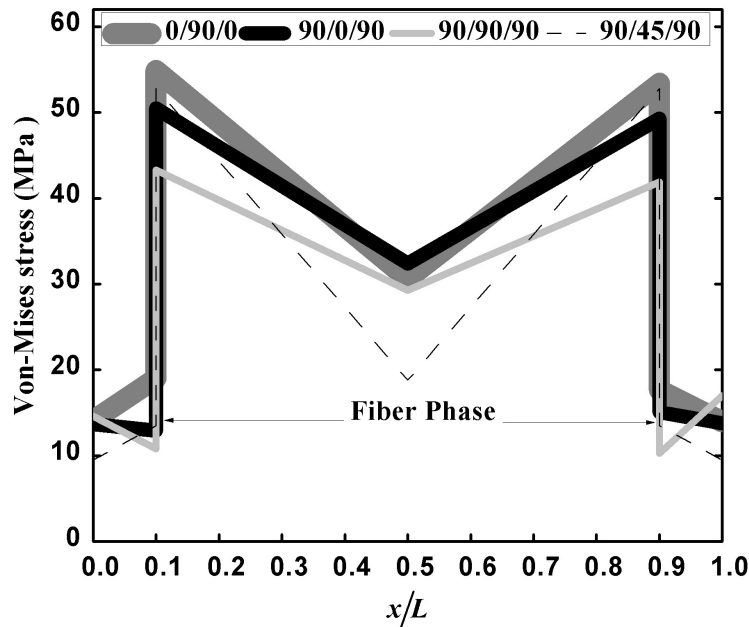


Figure 3.18 von Mises stresses on the free plane along the fibre and matrix zones

## CHAPTER 4

### BOND GRAPH MODELLING OF MOISTURE DIFFUSION AND STRESS ANALYSIS

The earlier studies have explained the importance of FRPs. The effect of fibre matrix architecture on the moisture diffusion and the resultant stresses induced in composites were discussed in the previous chapter. FEM was used for the moisture diffusion analysis. The moisture diffusion leads to expansion in matrix in comparison to fibres and this result in development of interfacial stresses.

In the present chapter, different fibre orientations in composites are modelled using bond graph modelling technique. As the stresses developed in composites are subjected to the displacement boundary conditions applied on them, plane strain displacement boundary conditions are applied other than the conditions applied in Chapter 3 to analyze composites behaviour under different displacement constraints.

#### 4.1 THREE-DIMENSIONAL MODELLING

In the discussed work, three-dimensional systems were modelled with FEM technique (Abaqus modelling software) as well as with the bond graph modelling technique (Symbol Shakti software). The Elastic and hygral properties of fibre and matrix are taken from experimental work [20] and these are presented in Table 4.1. These material properties are different than the properties used in Chapter 3.

**Table: 4.1** Materials properties for epoxy and resin [21]

Property	Fibre	Matrix
Modulus of Elasticity ( $E$ )	20 GPa	4.14 GPa
Poisson's Ratio ( $\nu$ )	0.33	0.36
Mass density ( $\rho$ )	1780 kg/m <sup>3</sup>	1310 kg/m <sup>3</sup>
Moisture Diffusivity ( $D$ , at $C= 1.48\%$ , $R_H = 85 \%$ )	0	$0.805 \times 10^{-14}$ m <sup>2</sup> /s
Solubility ( $S$ )	0	1

In this chapter, only two fibre orientations are considered. As seen from Figure 3.4 and Figure 3.7, it is observed that for (0/0/0) orientation, mass gain with respect to time is maximum and it is minimum for (90/90/90) orientation. The study of these two orientations

can easily predict the moisture diffusion in other orientations and can verify the results obtained in Chapter 3. Figure 4.1 shows three-dimensional models of (0/0/0/0) and (90/90/90/90) orientations.

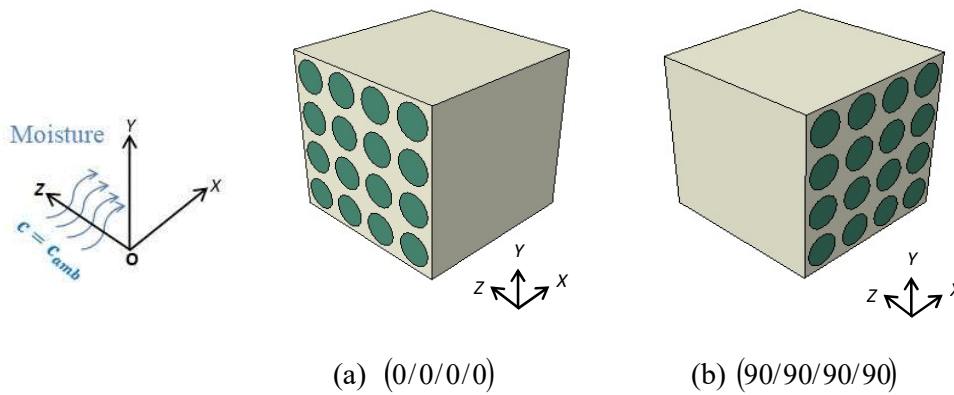


Figure 4.1 Moisture exposed plane and different three-dimensional fibre orientations models

In (0/0/0/0) orientation, all four layers of fibres are oriented along the direction of moisture ingress and in (90/90/90/90) orientation, all the layers of fibres are oriented in perpendicular direction to the moisture flow. Here, the fibre volume fraction ( $V_f$ ) is kept approximately equal to 0.5 and this is consistent across all the models even in Chapter 3. The fibre diameter is assumed to be of  $18\mu\text{m}$  and dimension of cubic models are  $a \times a \times a = 92\mu\text{m} \times 92\mu\text{m} \times 92\mu\text{m}$ .

## 4.2 MOISTURE DIFFUSION ANALYSIS

Initially, the cubic models are assumed to be completely dry in state (Refer Equation 3.1). Then, the left Y-Z ( $x=0$ ) plane is exposed to the environmental moisture with concentration of  $C_{\text{amb}}$ . The moisture exposed face is kept same throughout the analysis for all the orientations. This moisture condition is represented in Equation 3.2. No mass flux ( $\vec{J}$ ) is allowed to enter or leave through other planes except the one exposed to moisture (Refer Equation 3.3).

Fick's law is used to analyse moisture absorption following the assumptions taken in Chapter 3. The governing equations for finite element calculations are the extensions of Fick's first law. Fick's second law helps in finding a fundamental relation between dimensions of the diffusion domain and the time taken (Refer Equation 3.4). Simplification due to these assumptions ensures linear mass transport behaviour and had helped to detect the effect of other factors. After considering above assumptions, Fick's law is written as

Equation 3.5 and mass gain is calculated using Equation 3.6. For these analyses, all finite element code based on Fick's law is used and moisture concentration values taken are same as taken in Chapter 3. This modelling is also done using bond graph tools.

Bond graph is a graphical modelling technique that can portray different systems with different domains. Bond graph modelling was done using Symbol Shakti software. Figure 4.2 shows the graphical representation of three-dimensional fibre matrix models orientations using bond graph elements. Here,  $D$ ,  $c$ ,  $m$ ,  $L$  and  $A$  represent diffusivity, mass concentration, mass gain, length of elements and area of elements, respectively. In this model, concentration and mass flow rate are considered as effort and flow variable, respectively.

The compliance element is denoted by  $\frac{1}{A_i L_i}$  and resistive element is denoted by  $\frac{L_i}{DA_i}$ . The mass flow rate is denoted by SF element.

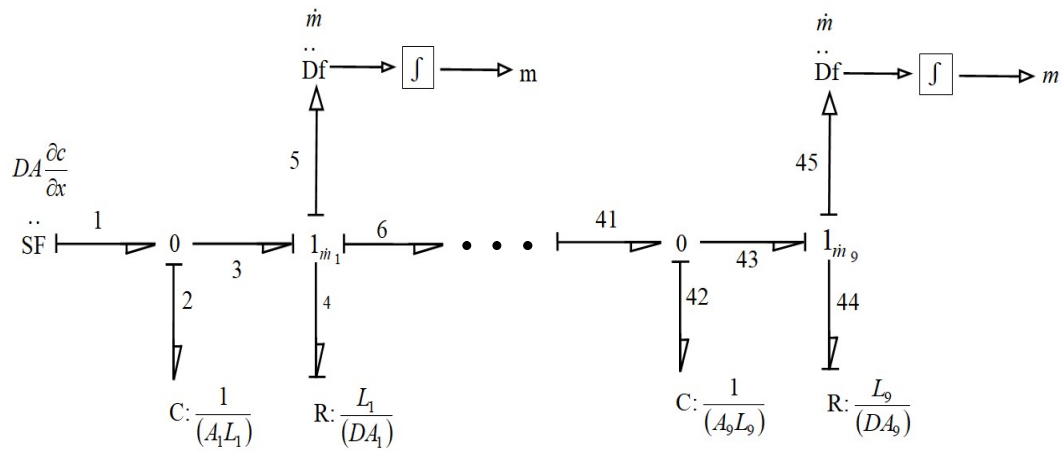


Figure 4.2 Three-dimensional fibre models using bond graph tools

In bond graph modelling, the cubic models were divided into nine elements. To represent three-dimensional models with (0//0/0/0) and (90/90/90/90) orientations, different bond graph elements were given different areas of cross sections depending on the presence of fibres. Figure 4.3 represents relationship between bond graph and Abaqus models. Table 4.2 represents the values of areas of cross-sections for bond graph elements taken for different fibre orientation models. Each element represents different area of cross sections ( $A$ ) but mass flux ( $\bar{J}$ ) is same. Equation 4.1 represents relationship between mass flux, diffusivity ( $D$ ) and concentration ( $c$ ).

$$\bar{J} = -D \cdot \frac{\partial c}{\partial x} \quad (4.1)$$

$$\dot{m} = \bar{J} \cdot A \quad (4.2)$$

The mass flow rate ( $\dot{m}$ ) was given as the source of flow and concentration ( $c$ ) acts as the effort in bond graph models. Figure 4.3 shows the approach of dividing Abaqus models into nine parts and further these parts are represented by each bond graph elements. Table 4.2 represents different cross sectional areas of different bond graph elements taken in order to mimic Abaqus models.

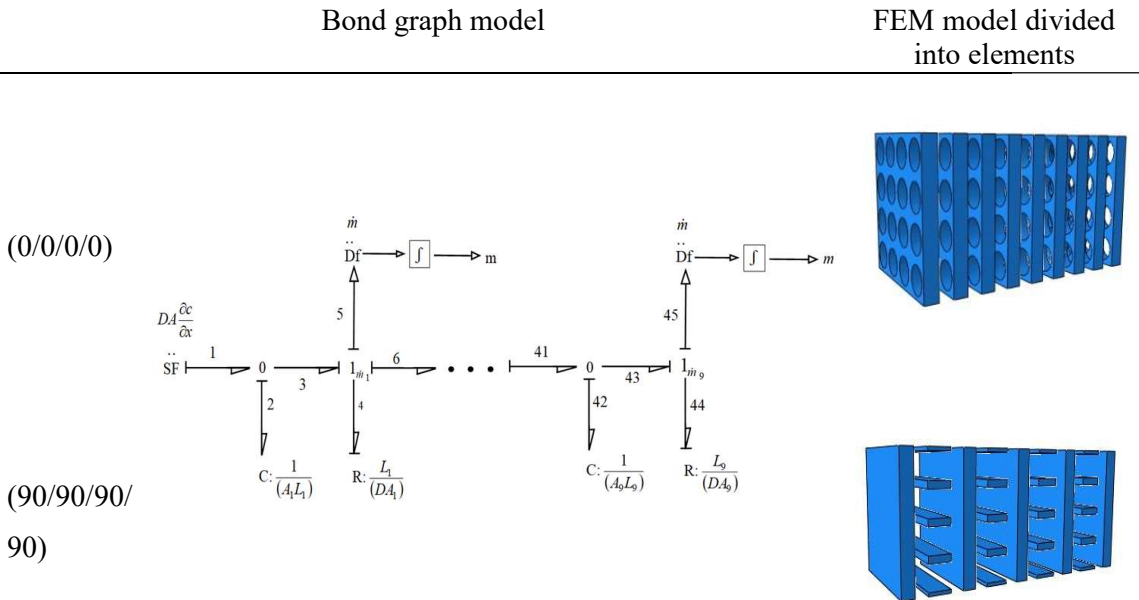


Figure 4.3 Representation of FEM models in terms of bond graph elements

Table 4.2 Areas of cross sections for different bond graph elements

Name of elements	0/0/0/0 (area in m <sup>2</sup> )	90/90/90/90 ( area in m <sup>2</sup> )
First		8464 x10 <sup>-12</sup>
Second		1840 x10 <sup>-12</sup>
Third		8464 x10 <sup>-12</sup>
Fourth		1840 x10 <sup>-12</sup>
Fifth	4394.56 x10 <sup>-12</sup>	8464 x10 <sup>-12</sup>
Sixth		1840 x10 <sup>-12</sup>
Seventh		8464 x10 <sup>-12</sup>
Eighth		1840 x10 <sup>-12</sup>
Ninth		8464 x10 <sup>-12</sup>

### 4.2.1 Results and Comparisons

From Equation 4.1, it was observed that mass flow rate depends on the area of cross section of elements. Therefore, for different elements with different areas of cross section of elements, time taken by the elements to reach maximum moisture concentration should be different. The mass gains in particular elements of different fibre orientation models with respect to time were calculated and plotted in Figure 4.4.

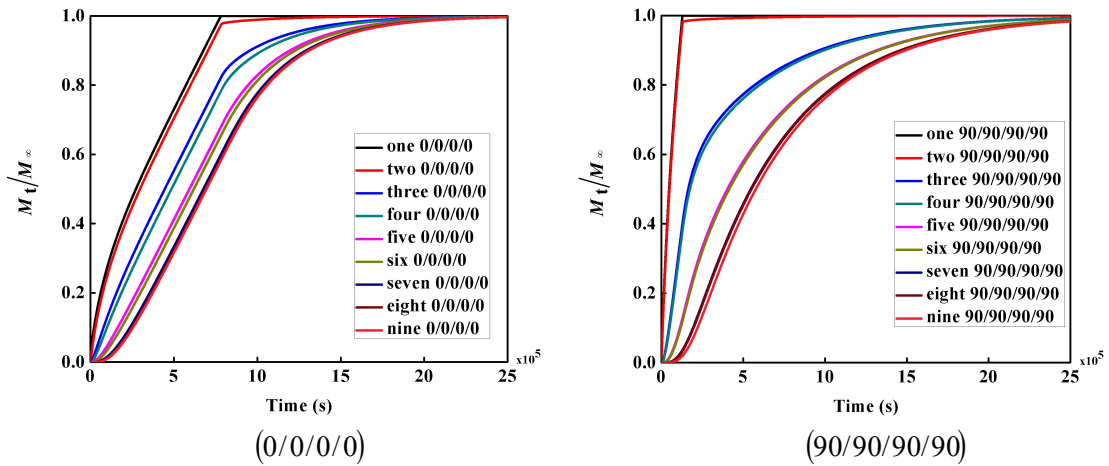


Figure 4.4 Ratio of saturated volume to the total volume for  $(0/0/0/0)$  and  $(90/90/90/90)$  orientation using Bond Graph

In Figure 4.5, comparison of mass gain profiles for  $(0/0/0/0)$  and  $(90/90/90/90)$  are plotted using bond graph results and initially, moisture progression is found to be more in  $(90/90/90/90)$  as moisture is acting on the resin rich face. But after some time when moisture encounters with perpendicular fibres, the moisture progression is delayed as fibres act as barrier. Therefore,  $(90/90/90/90)$  orientation takes more time in comparison to other orientation to reach saturation. Figure 4.5 suggests that for any values of diffusivity and solubility of matrix until it is not zero, the mass gain profiles in the  $(0/0/0/0)$  and  $(90/90/90/90)$  will follow the same trend as observed in Figure 3.4.

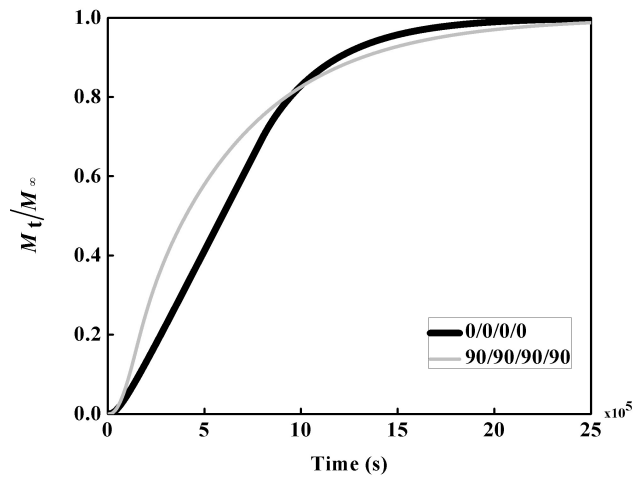


Figure 4.5 Ratio of saturated volume to the total volume for (0/0/0/0) and(90/90/90/90) orientation

For investigation of mass gain profiles reported in Figure 4.5, the mass gain profiles for (0/0/0/0) and (90/90/90/90) using bond graphs are compared with moisture diffusion FEM results as shown in Figure 4.6 and Figure 4.7. It has been observed that the FEM results are in exact favour with bond graph results. Therefore the three dimensional models initially modelled in Abaqus verifies models modelled in bond graphs as the moisture diffusion analysis shows the same trends of moisture ingress.

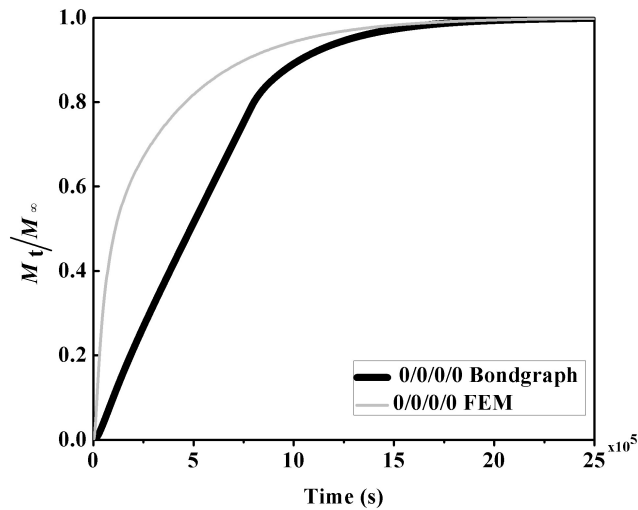


Figure 4.6 Comparison of moisture progression graphs between bond graph method and FEM analysis

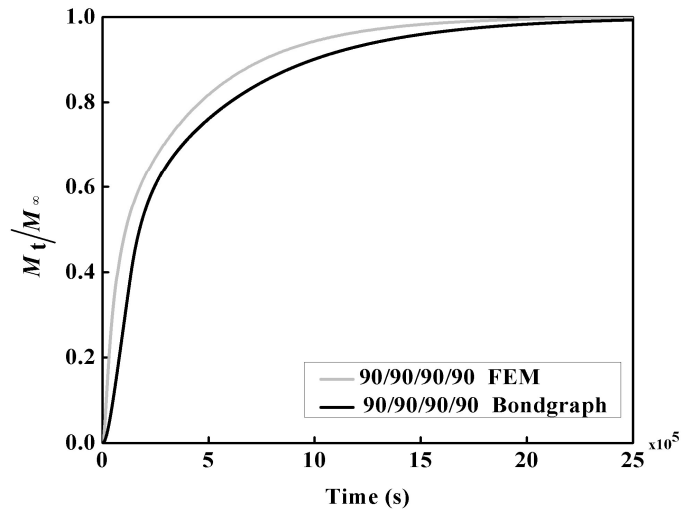


Figure 4.7 Comparison of moisture progression graphs with FEM analysis

### 4.3 HYGRO-MECHANICAL ANALYSIS

The discussed work reports the stresses induced in the composite after moisture absorption. The three-dimensional models considered are same as the models considered for the moisture diffusion analysis. Hygro-mechanical stress analyses are already considered in Chapter 3. But, stresses induced in the composite materials are subjected to the displacement boundary conditions imposed on the composite materials. Composite materials behave differently under different boundary conditions. In Chapter 3, concentric cylinder assemblage boundary conditions were considered and the stresses induced were calculated and analysed. In this Chapter, plane strain displacement boundary conditions are applied constraining the displacements along  $x$ ,  $y$ ,  $z$  directions. The displacements along  $x$ ,  $y$ ,  $z$  directions are denoted by  $U_1$ ,  $U_2$ ,  $U_3$ , respectively.

#### 4.3.1 Plane Strain Conditions

Plane strain conditions (Figure 4.8) are set of boundary conditions that are mainly used to calculate and analyse fracture or deformation in materials and this helps in inspection of changes in size and shape along only one plane. It is a state of strain on a material when strain components are acting along one plane and are not equal to zero.  $\varepsilon_x$  and  $\varepsilon_z$  represent strain in  $x$ ,  $y$  directions  $\gamma_{xy}$  represents shear strain in  $x,y$  directions and they may not have zero values.

$$\varepsilon_x = \frac{\partial u}{\partial x}, \varepsilon_y = \frac{\partial v}{\partial y}, \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \quad (4.3)$$

$$\varepsilon_z = \frac{\partial w}{\partial z} = 0, \quad \gamma_{xz} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} = 0, \quad \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} = 0, \quad (4.4)$$

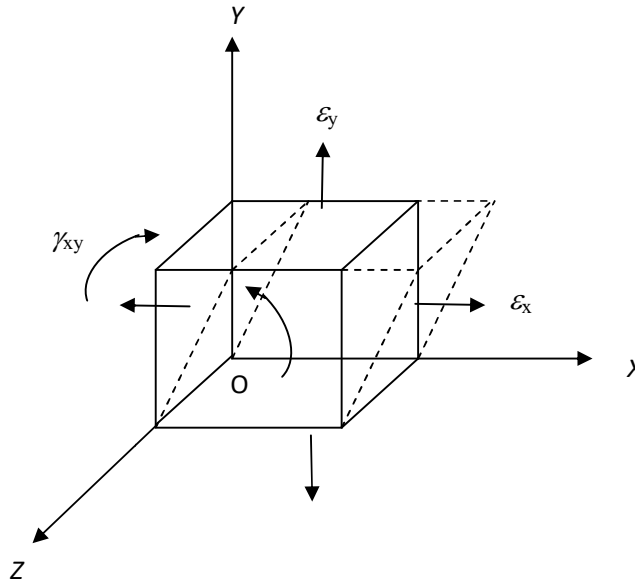


Figure 4.8 Application of plane strain conditions on cubic model

#### 4.3.2 Bond Graph Modelling for Stress Analysis

Different bond graph modelling is done for the application of plane stress conditions on fibre matrix three-dimensional models. Bond graph model for stress analysis (Figure 4.9) is similar to three-dimensional fibre models using bond graph tools as shown in Figure 4.2. The concentration at each node is calculated and this concentration is used to find stress at the nodes using TF element with modulus of  $1/(\beta E)$ . Here,  $D$ ,  $c$ ,  $m$ ,  $L$  and  $A$  represent diffusivity, mass concentration, mass gain, length of elements and area of elements, respectively.

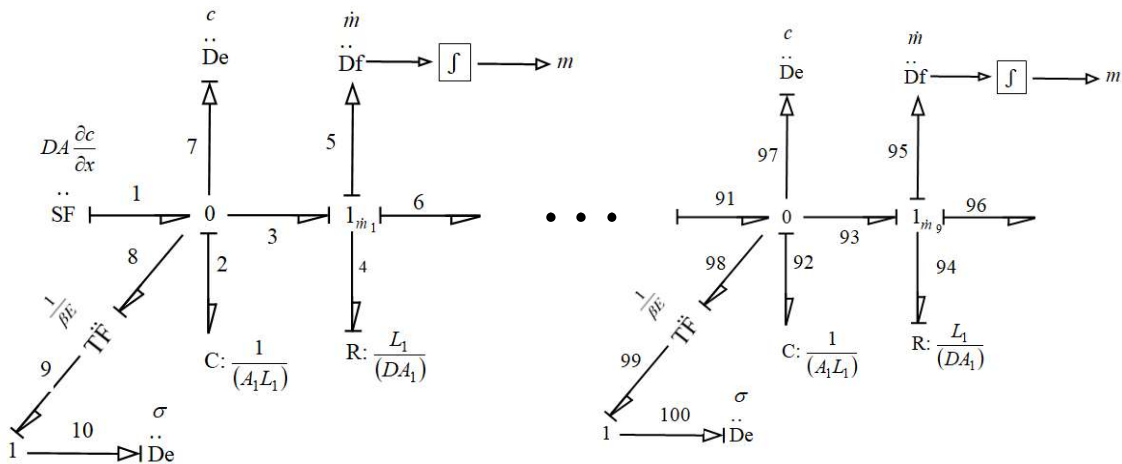


Figure 4.9 Bond graph model for three-dimensional fibre matrix models

### 4.3.3 Boundary Conditions for Stress Analysis

The planes perpendicular to the plane which is exposed to moisture are fixed. By constraining face abcd and the face efgh, the plane strain boundary conditions (Figure 4.10) applied are given by

$$U_1=0 \text{ (on plane adeg i.e. } x = 0) \quad (4.5)$$

$$U_3= 0 \text{ (on plane efgh and on plane abcd i.e. } z = 0) \quad (4.6)$$

$$U_1=U_2=U_3=0 \text{ (at corner } a (0, 0, 0) \text{ and at } g (0, 0, -a)) \quad (4.7)$$

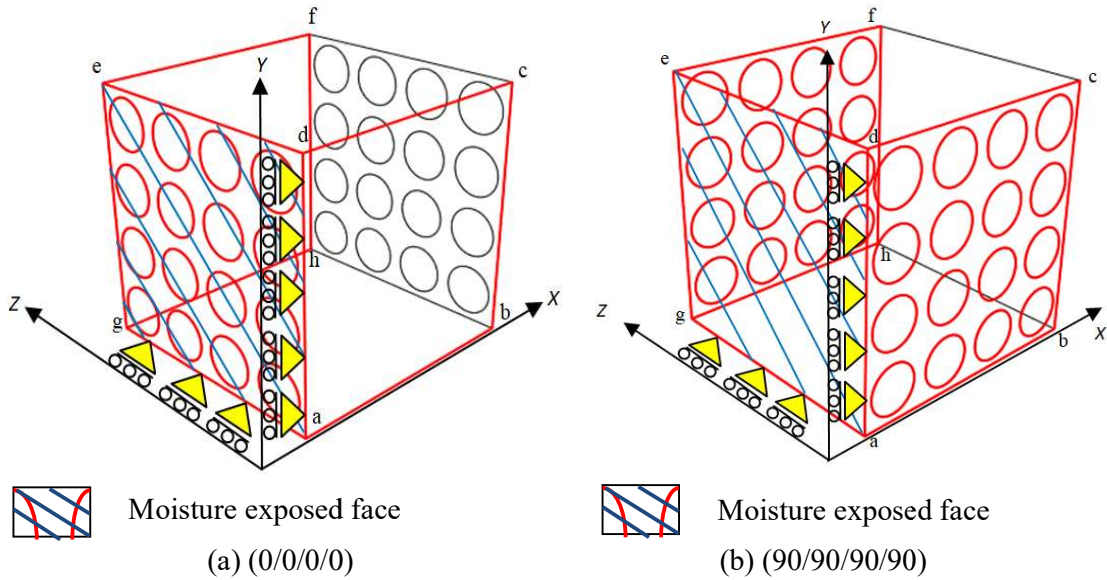


Figure 4.10 Moisture boundary conditions along with displacement boundary conditions

Along with the above mentioned boundary conditions, moisture boundary conditions are same as in moisture diffusion analysis. As displacement along z-direction is zero, there is a controlled expansion in composites. Therefore, the strain components are given by

$$\varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0 \quad (4.8)$$

$$\gamma_{xz} = \gamma_{yz} = 0, \tau_{xz} = \tau_{yz} = 0, \varepsilon_z = 0 \quad (4.9)$$

$$\varepsilon_z = \frac{\sigma_z}{E} - \mu \frac{(\sigma_x + \sigma_y)}{E} = 0 \quad (4.10)$$

$$\sigma_z = \mu (\sigma_x + \sigma_y) \quad (4.11)$$

Using Equation 3.1, FEA is solved to calculate concentration on a particular node and from the resultant concentration on one node, further hygral strain ( $\varepsilon_h$ ) is calculated as

$$\varepsilon_h = \beta_h C \quad (4.12)$$

Using properties given in Table 4.1, the stress developed in composite materials on saturation of moisture is calculated as

$$\sigma_{\text{matrix}} = \beta_h c E \quad (4.13)$$

To calculate and analyse the effect of moisture and displacement boundary conditions together, the coupled temperature displacement module provided in Abaqus is used. Here, moisture diffusivity is provided in terms of thermal diffusivity as used in Chapter 3. Thermal diffusivity is calculated as

$$D_t = K / \rho c_p \quad (4.14)$$

Where  $D_t$  represents equivalent thermal diffusivity,  $\rho$  represents mass density and  $c_p$  represents specific heat [20]. The mesh elements are displacement and thermally coupled and the stresses plotted in Figure 4.11 are calculated on the fixed face efgh for both the orientations.

#### 4.3.4 Results and Comparisons

In Figure 4.12, the von Mises stresses developed in (0/0/0/0) and (90/90/90/90) are shown. It is observed that the stresses reach their maximum value in (90/90/90/90) orientation much earlier in comparison to (0/0/0/0) orientation because in (90/90/90/90), initially more matrix region is exposed to moisture in comparison to (0/0/0/0). Therefore, the results are perfectly in favour of Equation 4.13 and the results are directly proportional to the moisture concentration. Figure 4.12 shows the comparison of bond graph stress results for (0/0/0/0) and (90/90/90/90) orientation.

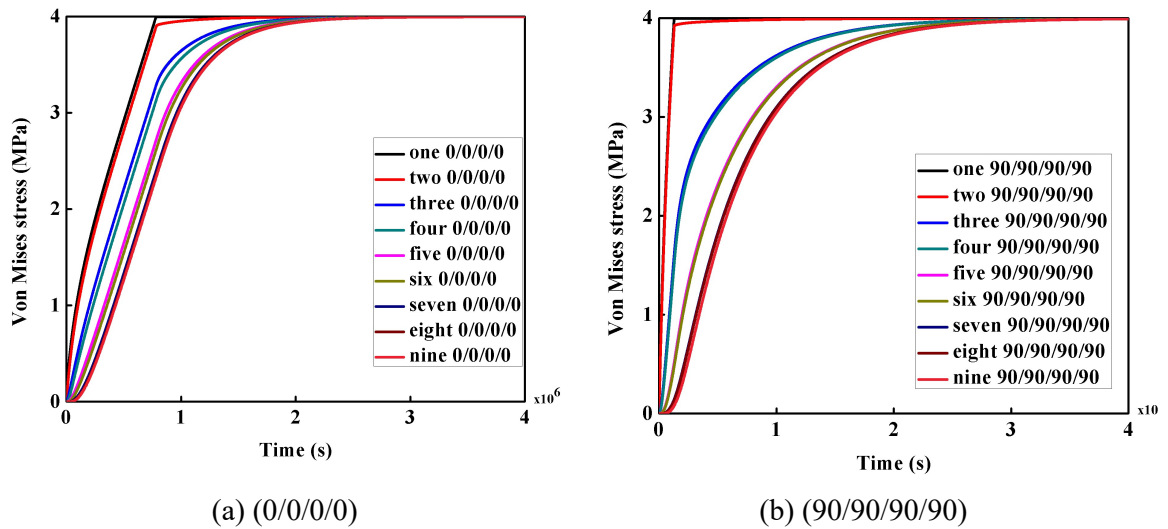


Figure 4.11 Stresses produced on the fixed face due to moisture diffusion

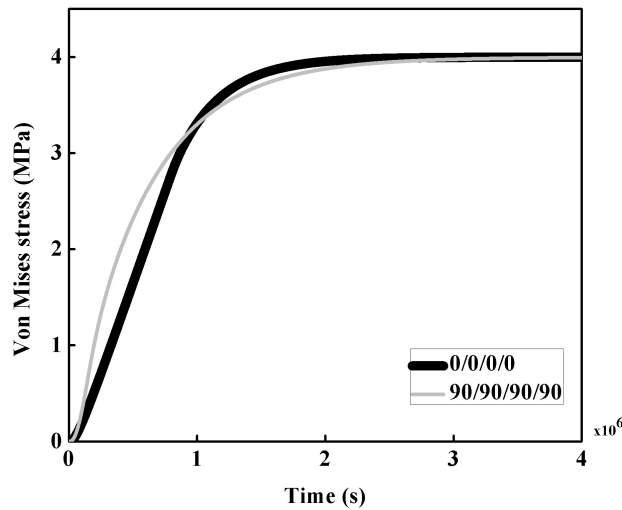


Figure 4.12 von Mises stresses on the fixed plane along the fibre and matrix zones

Figure 4.13 represents the comparison of stresses calculated using FEM analysis with the help of Abaqus software to the theoretical stresses calculated using bond graph technique. For (0/0/0/0) orientation, the stresses obtained from both the analyses is same. As the fixed face of (0/0/0/0) orientation does not have fibres coming out through it as there are no interface regions for (0/0/0/0) orientation on the face where stress is calculated. As matrix regions are perfectly modelled by bond graph, the stresses produced in bond graph model are in correct favour with stresses developed in Abaqus model. From Figure 4.14, it can be observed that interface regions are the critical regions where mostly stresses are developed on moisture absorption because there is a difference between coefficients of expansion of both the materials. In (90/90/90/90) orientation, fixed face has sixteen interface regions in

comparison to zero interface regions in (0/0/0/0). Therefore, more stresses are developed in (90/90/90/90) orientation and this can be easily observed from Figure 4.14. There is a slight difference in the stresses calculated using FEM and bond graph as using FEM approximated results are obtained.

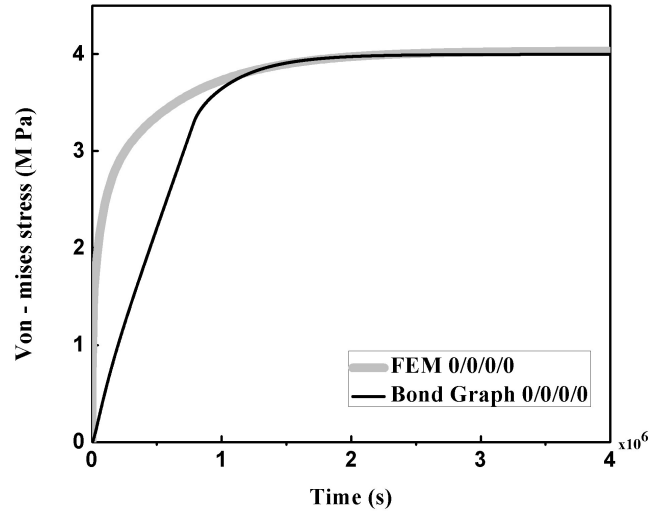


Figure 4.13 Comparison of von-Mises stresses on the fixed plane between FEM and bond graph analysis

Using proper bond graph techniques, the stresses in (0/0/0/0) and (90/90/90/90) can be predicted to a very good extent.

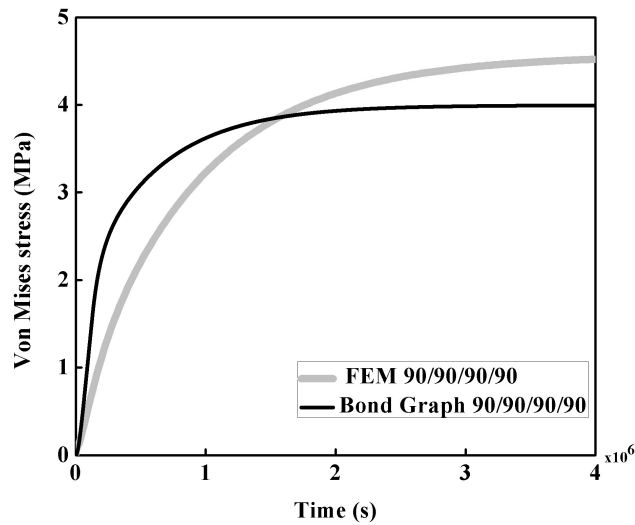


Figure 4.14 Comparison of von Mises stresses on the fixed plane with FEM calculated stresses

## CHAPTER 5

### EXPERIMENTATION FOR MOISTURE DIFFUSION PROCESS IN GLASS FIBRE COMPOSITE MATERIAL

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A short experimental investigation was done towards the end of this research work. The objective of this experiment was to compare the results of analytical findings with the experimental results. In Chapter 3, moisture diffusion analysis is conducted to find out the effect of fibre orientations on the moisture absorption process in three-dimensional models. Figure 5.1 shows a flowchart of key activities performed during this experiment.

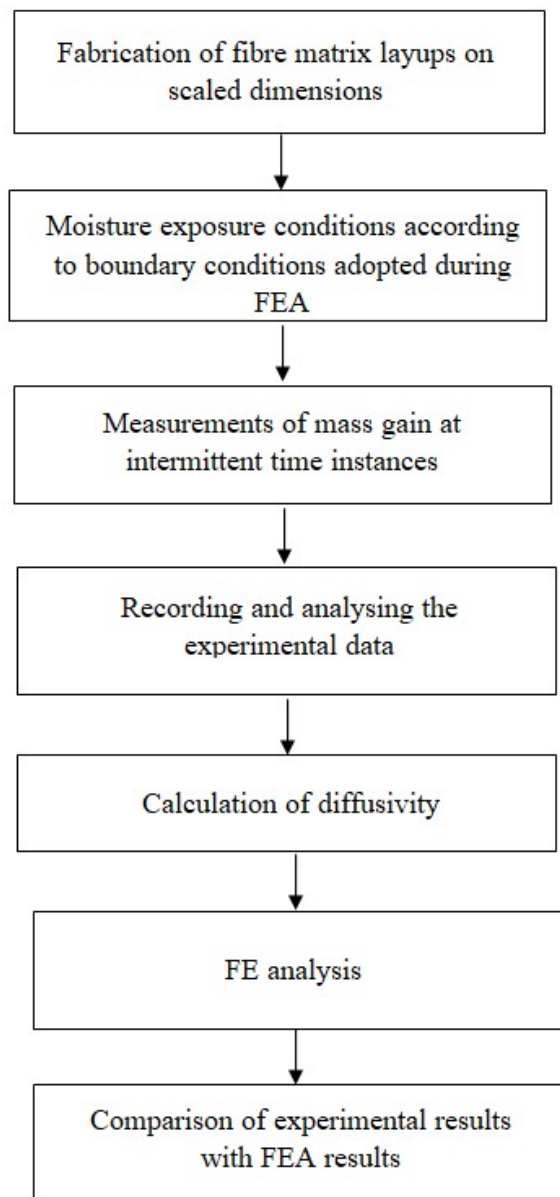


Figure 5.1 Flowchart of experimental methodology

## 5.1 MATERIALS USED

The fibres matrix laminates were manufactured using Epoxy resin (Grade LY-556), Hardener (Grade HY-951) as matrix materials, E-glass fibres were used as reinforcing materials and araldite (Grade AW-106) adhesive epoxy for sealing purposes. The unidirectional E-glass fibres were procured from Owens Corning (Mumbai, India) and Epoxy resin and Hardener were purchased from Huntsman Corporation (Bangalore, India). Figure 5.2 (a–c) shows the resin, hardener and glass fibres, respectively used in the experiments. In order to mimic the moisture boundary conditions applied during FEA, araldite standard epoxy adhesive sealant (AW-106) was used to seal all the faces of the specimens except the face to be exposed to moisture in Figure 5.2 (d) and this face is water as well as heat proof.



(a) Epoxy resin



(b) Hardener



(c) Glass fibres woven mat



(d) Sealant

Figure 5.2 Materials used: (a) Epoxy resin (b) hardener (c) glass fibres and (d) sealant

### 5.1.1 Mechanics of Diffusion Inside Resin

Total volume of epoxy resin is the addition of free volume and occupied volume which includes Vander Waal's volumes as well as volumes associated with thermal mobility. At temperatures higher than glass transition temperature, free volume in the epoxy gets distributed throughout the volume. These free volumes are produced due to fluctuations in density at different regions within the resin itself. Free volumes are the less dense regions with free volumes or holes bigger than water molecules. These holes attract water/moisture and are responsible for hydrophilic nature of epoxy resin materials [41]. Figure 5.3 shows polymer chains of epoxy resin. Water gets diffused through these polymer chains. On the contrary, in case of glass fibres there are not enough large free volumes that can allow absorption of water molecules. Therefore, they are hydrophobic in nature [41].

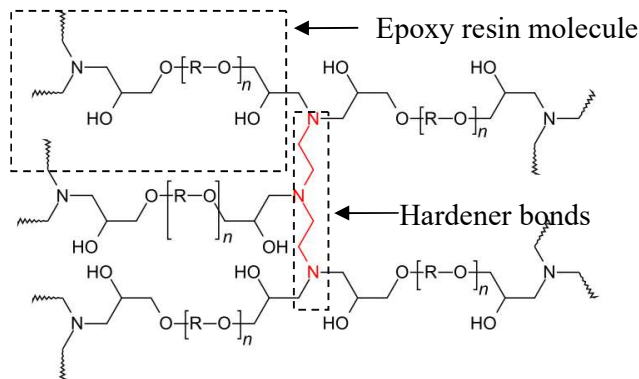


Figure 5.3 Chemical chain in which hardener molecule bonds binds the epoxy resin molecules

## 5.2 FABRICATION PROCEDURE, SPECIMENS AND THEIR SCALED PROPORTIONS

In a typical fibre matrix system, the fibres are of size 10–30 microns. The experiment was conducted on the scaled sized specimens. Two analogous models used to represent the 0/0/0 and 90/90/90 orientations were fabricated. All the dimensions were scaled to 1:1000. It means that a fibre diameter of 22 microns on a scaled experimental specimen measures 22 mm. For the FEA simulations, the representative volume element (RVE) size is kept as  $(81\mu\text{m}\times 81\mu\text{m})$ . Hence, the specimen size is  $(81\text{mm}\times 81\text{mm})$  for the experimental investigations. Both resin and hardener were mixed in a ratio of 10:1, respectively. Figure 5.4 shows the actual mixing of epoxy and hardener with the help of stirrer.



Figure 5.4 Mixing of epoxy resin and hardener

To fabricate the cubic specimens, leak proof cardboard moulds were prepared according to the dimensions and tolerances of specimens; the circular rolls of glass fibre sheets were placed in all the layers according to their orientations. All the edges of the mould were glued together and were made leak proof. The fibre bundles were placed as reinforcement, three in each layer. Figure 5.5 shows the moulds and fibre arrangement. The mixture of epoxy resin and hardener was poured from the top of the leak proof mould as prescribed under the manufacturer's catalogue. These moulds were kept for 24 hours at ambient temperature for curing before they were subjected to humid environments.



Figure 5.5 Cardboard moulds used to make specimens

Later, these cardboard moulds were machined so that external layers of cardboard can be removed and cleaned fibre matrix layers can be achieved. Figure 5.6 represents fibre matrix layers. Finally, all three layers were stacked to each other in a sequence one above other to obtain three-dimensional fibre matrix composite specimens with desired fibre

orientations. Figure 5.7 shows the specimens along with three-dimensional Abaqus models for (0/0/0) and (90/90/90) orientations.



Figure 5.6 Specimen of composite materials

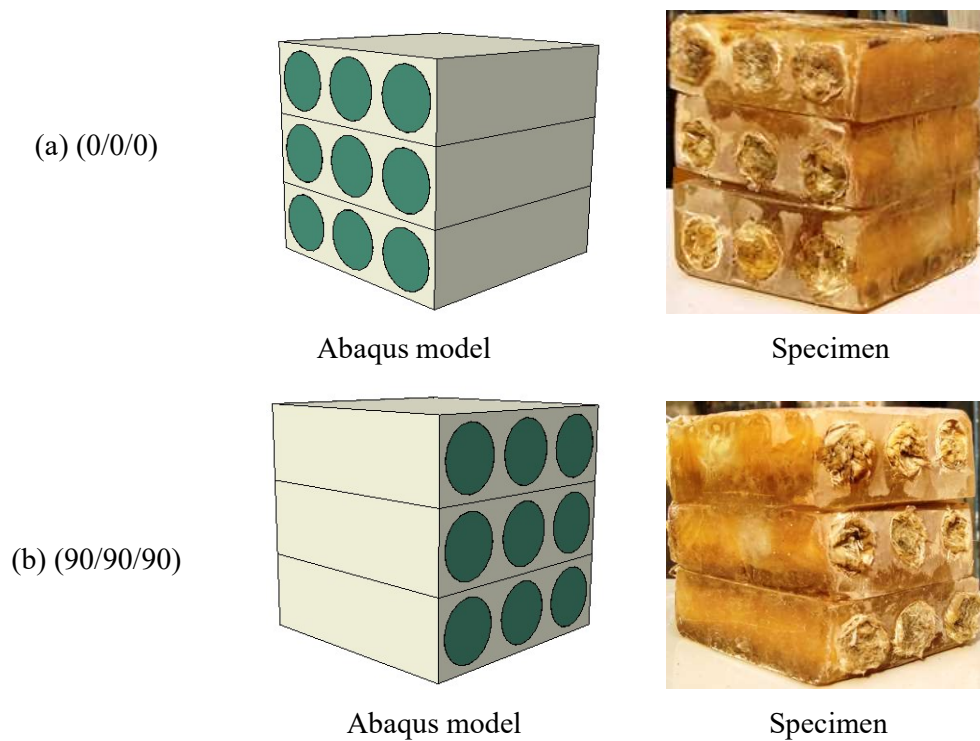


Figure 5.7 Specimens for (0/0/0) and (90/90/90) orientations resembling Abaqus models

Figure 5.8 shows the representation of moisture boundary conditions applied for (0/0/0) and (90/90/90) orientations. For experimental study, all the faces of the specimens were sealed with adhesive epoxy except the face to be exposed to moisture. This adhesive epoxy is

heat as well as water resistant. In Figure 5.8,  $X$ - $Y$  planes of specimens are exposed to moisture and all other faces are sealed and are insulated from environmental moisture.

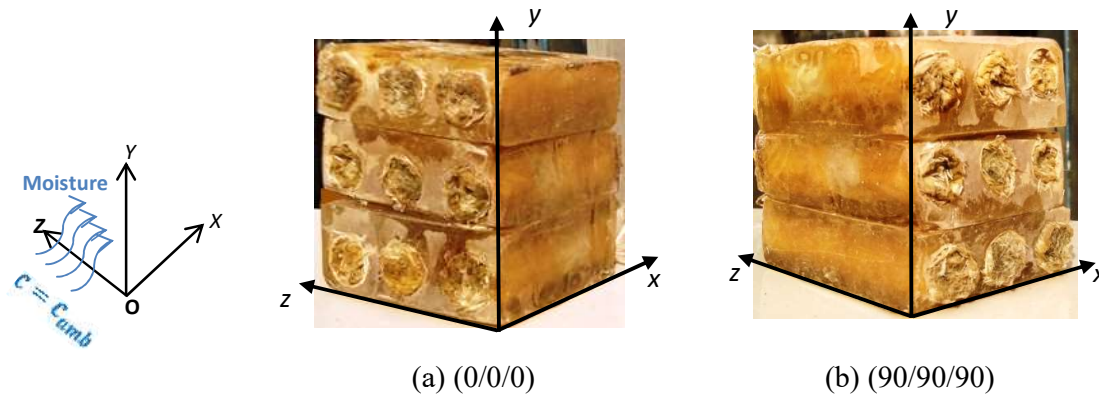


Figure 5.8 Moisture exposed faces for (0/0/0) and (90/90/90) orientations

### 5.3 EXPERIMENTAL SETUP

The actual degradation in composites can be measured more accurately through natural environment exposures. In this work, accelerated degradation was performed to mimic the environmental exposure. Figure 5.9 shows cryostat and precision weighing machine used in this experiment. Cryostat is an enclosed chamber which has a liquid bath where fixed temperatures can be maintained.



Figure 5.9 (a) Cryostat and (b) precision weighing machine

The specimens with 0/0/0 and 90/90/90 orientations were placed from initial dry state into the accelerated environment. The specimens were taken out from the cryostat after a fixed interval of time and mass gain was calculated. While calculating the mass gain, proper care was taken because as soon as the specimens were taken out from the cryostat,

desorption got started. Therefore, use of plastic bags became very important. Most of the part of specimens was covered by them to avoid evaporation of water.

The precision weighing machine that was used for measuring mass gain was kept close to the cryostat because more the time taken in measuring the mass gains, more were the chances of error.

#### 5.4 CALCULATION OF DIFFUSIVITY

For calculation of the Fickian diffusivity ( $D_f$ ), Fickian saturation values were obtained. Here, the fibre orientation and geometrical effects of composites were assumed to be neglected and it was assumed that Fickian diffusion coefficient was same for all directions as it was found to be in resin only i.e.  $D_x = D_y = D_z$ , where  $D_x, D_y$  and  $D_z$  represents diffusivity in x, y, z directions respectively. In calculation of the diffusivity, edge factor plays a significant role. For the compensation of the edge effect, the edge correction factor is calculated [43, 44]. The edge correction factor (ECF) is formulated as

$$ECF = 1 + 0.54 \times \frac{h}{l} + 0.54 \times \frac{h}{w} + 0.33 \times \frac{h^2}{l \times w} \quad (5.1)$$

Where,  $l, w, h$  represent length, width and thickness of the specimens taken, respectively. In order to calculate the diffusion coefficients mass gain % with respect to time for which specimen was immersed in water was studied. After analysing the plot, the points with approximated linear behaviour were chosen for finding out of diffusivity in Figure 5.10 and diffusivity was calculated using Equation 5.2.

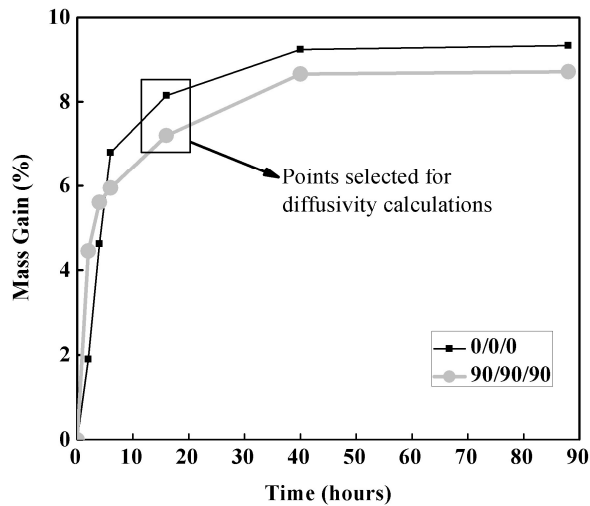


Figure 5.10 Mass gain (%) vs. time of immersion

$$D_f = \frac{g^2 \times h^2}{M^2 \times 16\pi \left( 1 + 0.54 \times \frac{h}{l} + 0.54 \times \frac{h}{w} + 0.33 \times \frac{h^2}{lw} \right)} \quad (5.2)$$

Where,  $D_f$  represents Fickian diffusivity,  $g$  represents mass gain and  $M$  represents mass flow rate in Equation 5.2 and  $h$ ,  $l$ ,  $w$  were thickness, length and width of samples, respectively [42, 43]. In this study, cubic specimens were taken, therefore,  $h$ ,  $l$  and  $w$  were equal. Edge effect plays a significant role in calculation of diffusivity. Edge correction factor was calculated to eliminate the edge effect in calculation of diffusivity. For verification of the experimental results, this diffusivity value obtained was used for simulation work and later results were compared.

### 5.5 EXPERIMENTAL VALIDATION

Figure 5.11 shows the relative mass gain  $M_t/M_\infty$  with respect to time. Here,  $M_t$  was instantaneous mass and  $M_\infty$  was the saturated mass of the composite. It can be noticed that initially 90/90/90 mass gain profile was left to the 0/0/0 orientation mass gain profile. This was primarily due to the resin phase that gets saturated before the moisture flow encounters fibre as a barrier. But, later as soon as the moisture encounters with the fibres which acted as a barrier to moisture flow, the difference in mass gain got more distinct and moisture diffusion was found to be more faster in 0/0/0 when compared to 90/90/90.

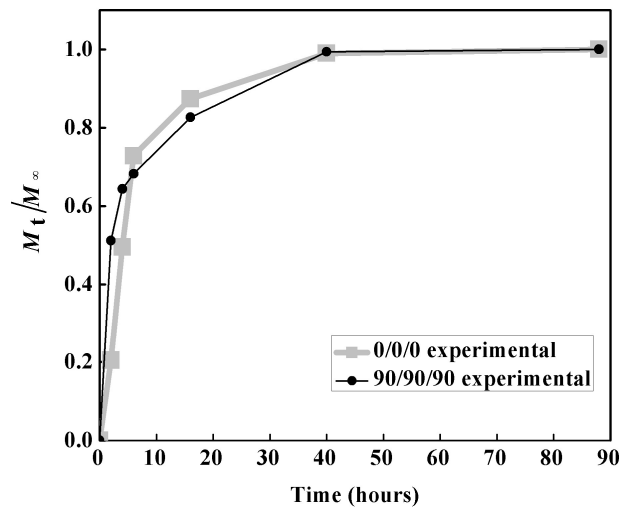


Figure 5.11 Ratio of saturated volume to the total volume for (0/0/0) and (90/90/90) orientations

Figure 5.12 shows the comparison of  $M_t/M_\infty$  plot for experimental and simulation work. It concludes that experimental work completely favours the simulation data. For both experimental and analytical data, plotted initially there was more moisture absorption in (90/90/90) in comparison to (0/0/0). Later, it was found that moisture absorption lags behind in (90/90/90) as moisture ingress encounters fibre in perpendicular direction that obstructed the moisture flow.

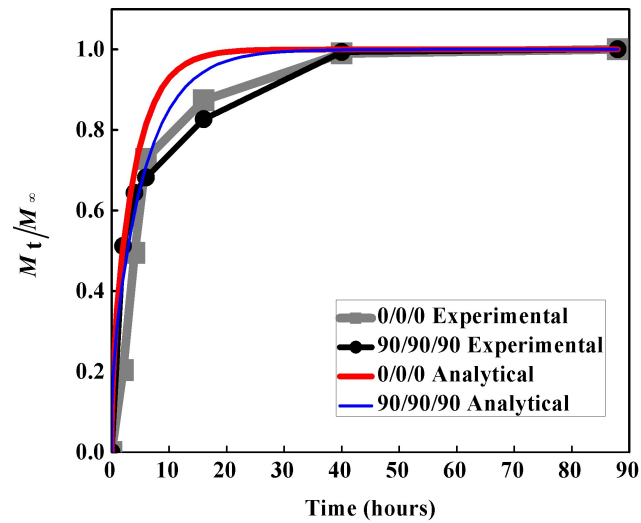


Figure 5.12 Comparison of experimental and analytical results



## CHAPTER 6

### CONCLUSIONS

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#### 6.1 CONCLUSIONS

A comprehensive analysis is conducted on the three-dimensional models of fibre matrix composite multiple directional laminates having fibre orientations along and across the flow of moisture ingress. The two stage analysis is conducted first to evaluate the performance of different orientations for the diffusion response and then the stress behaviour is analysed for the similar orientations subsequently. The theoretical results from FEA and bond graph are validated with the experimental results. There are many important conclusions which can be drawn from this study:

- Moisture diffusion behaviour is noted to be different when moisture flows across and along the fibre. The results show that mass flow rate is faster in the orientations having more fibres along the moisture flow in comparison to the orientations having fibres perpendicular to the moisture flow. Among all the studied orientations it is found that the diffusion rate is lowest for the orientation (90/90/90) having all the fibres perpendicular to the moisture diffusion flow.
- The 90/90/90 orientation also yields least stresses owed to a higher number of load bearing fibres on the unexposed planes as compared to other orientations with an equivalent fibre volume fraction.
- The angle ply orientations can offer a higher moisture resistance as compared to the cross ply orientations with the fibres along the direction of mass flow, at the same time the stress behaviour of these orientations is debatable because of their inability to bear the loads due to their directional obliquity.
- The axial stresses evaluated alongside the fibre and matrix and their ratios at the interface using finite element analysis are found in good agreement with CCA model.
- The 90/90/90 orientation proves to be front runner for the design consideration owing to its diffusion and diffusion induced stress behaviour.

The study also shows that stresses are in significant relations with the considered boundary conditions. Although an important issue in designing any multidirectional laminate is to have an optimum mix of layups for the required durability. Investigating the three dimensional composite microstructures locally for the given loading conditions can provide many

important structural design clues and a trade-off can be reached between different architectures for the optimal performance.

## 6.2 FUTURE SCOPE OF THE THESIS WORK

Although significant efforts have been made to consider all the factors that can effect the moisture absorption and the resultant stresses induced in composites. But still there is enough scope for further advancement in research. Some suggestions for future development are as follows:

- In spite of considering value of moisture diffusivity to be constant, variable diffusivity on the entry of moisture can be considered for more realistic results
- Influence of moisture diffusion in fibre would also be interesting study to be carried out
- While studying, the moisture diffusion analysis, chemical reaction between the absorbed moisture and composites can be also be included.
- There are still possibilities to consider the effect of other fibre orientations, other than considered here.
- Effect of different displacement boundary conditions other than used here can also be a topic of study
- Stresses analysis after considering transversely orthotropic properties of fibres can be done
- Study of failures of composites due to fracture of composites at interfaces due to development stresses can be a topic of study

## REFERENCES

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- [1] Vaddadi P, Nakamura T and Singh RP, (2003). Inverse analysis for transient moisture diffusion through fibre-reinforced composites, *Acta Materialia*, 51,177.
- [2] Sharma A. Environmental Degradation of Glass Fibre Reinforced Polymer Composites. M.E. Thesis, Thapar institute of Engineering and Technology, Patiala, India, 2009.
- [3] Mukherjee A, Karmakar R and Samantaray AK. *Bond graph in modeling, simulation and fault identification*. Florida USA: CRC Press, 2006.
- [4] Lahkar BK. Bond Graph Aided Hydraulic Flow Model of Plant in Response to Physical and Environmental Factors. M.E. Thesis, Thapar Institute of Engineering and Technology, Patiala, India, 2016.
- [5] Fuqua MA, Huo S and Ulven CA, (2012). Natural fibre reinforced composites, *Polymer Reviews*, 52 (3), 259–320.
- [6] Wang H *et al.* (2012). Critical factors on manufacturing processes of natural fibre composites, *Composite Part B Engineering*, 43(8), 3549–3562.
- [7] Saharudin MS, *et al.* (2016). The degradation of mechanical properties in polymer nano-composites exposed to liquid media - a review, *RSC Advances*, 6 (2), 1076–1089.
- [8] Vilaplana F, Stromberg E and Karlsson S (2010). Environmental and resource aspects of sustainable bio composites, *Polymer Degradation and Stability*, 95, 2147–2161.
- [9] Bakis C *et al.* (2002). Fibre-reinforced polymer composites for construction-state-of-the-art review. *Journal of Composites for Construction*, 6(2), 73–87.
- [10] Mosallam AS *et al.* (2015). Polymer composites in construction: an overview. *Journal of Material Science Engineering*, 2(1), 25.
- [11] Acha BA, Reboredo MM and Marcovich NE (2007). Creep and dynamic mechanical behavior of PP-jute composites: effect of the interfacial adhesion. *Composites Part A Applied Sciences and Manufacturing*, 38, 1507–1516.
- [12] Hong B, Xian. G and Wang Z (2018). Durability study of pultruded carbon fiber reinforced polymer plates subjected to water immersion. *Advances in Structural Engineering*, 21(4), 571–579.
- [13] Korkees F, Alston S and Arnold C, (2017). Directional diffusion of moisture into unidirectional Carbon Fiber/Epoxy composites: experiments and modeling, *Polymer composites*,(Online)
- [14] Joliff Y *et al.* (2014). Study of the moisture/stress effects on glass fibre/epoxy composite and the impact of the interphase area. *Composite Structures*, 108, 876–885.

- [15] Radha JC and Ranganathaiah C (2008). Effect of the fiber orientation on the sorption kinetics of seawater in an epoxy/glass composite: A free-volume microprobe study. *Journal of Applied Polymer Science*, 109(2), 1302–1309.
- [16] Ramezani Dana H *et al.* (2014). Numerical and Experimental investigation of Hygro-Mechanical States of Glass Fiber Reinforced Polyester Composites Experienced by FBG Sensors, *Composite Structures*.14, 185–188.
- [17] Bonora N and Ruggiero A (2006). Micromechanical modeling of composites with mechanical interface – Part 1: Unit cell model development and manufacturing process effects. *Composite Science and Technology*, 66(2), 314.
- [18] Vaughan TJ and McCarthy CT (2011). Micromechanical modelling of the transverse damage behaviour in fibre reinforced composites. *Composite Science and Technology*, 71, 388.
- [19] Pan Y, Xian G and Li H (2017). Numerical Modeling of Moisture Diffusion in an Unidirectional Fiber-Reinforced Polymer Composite. *Polymer composites*, (Online).
- [20] Arnold JC, Alston SM and Korkees F (2013). An assessment of methods to determine the directional moisture diffusion coefficients of composite materials. *Composites Part A*, 55, 120–128.
- [20] Jain D, Mukherjee A and Kwatra N (2014). Local micromechanics of moisture diffusion in fiber reinforced polymer composites. *International Journal of Heat Mass Transfer*. 76,199.
- [21] Jain D, Mukherjee A and Kwatra N (2015). Effect of Fibre Topology on Hygro-Mechanical response of polymer matrix composites. *International Journal of Heat Mass Transfer*. 86, 787.
- [22] Loha WK *et al.* (2005). Modelling anomalous moisture uptake, swelling and thermal characteristics of a rubber toughened epoxy adhesive. *International journal of Adhesion and Adhesives*. 25, 1–12.
- [23] Heshmati M , Haghani R and Al-Emrani M (2017). Durability of bonded FRP-to-steel joints: Effects of moisture, de-icing salt solution, temperature and FRP type *Composites Part B: Engineering*, 119,153-167
- [24] Wang W, Sain M and Cooper PA (2006). Study of moisture absorption in natural fibre plastic composites. *Composites Science and Technology*. 66, 379–386.
- [25] Naceri A (2007). Moisture absorption and mechanical and acoustic responses in shear of a glass fibre fabric/epoxy resin composite. *Mechanics of Composite Materials*. 43, 5.
- [26] George J, Bhagawan and SS Thomas S (1998). Effects of environment on the

- properties of low-density polyethylene composites reinforced with pineapple-leaf fibre. *Composite Science and Technology*. 58, 1471–85.
- [27] Stark N (2001). Influence of moisture absorption on mechanical properties of wood flour–polypropylene composites. *Journal of Thermoplastic Composite Materials*. 14, 421–32.
- [28] Bajpai SK, Mary G and Chand N, The use of cotton fibres as reinforcements in composites, *Biofiber Reinforcements in Composite Materials*, India: Woodhead Publishing, 2015, 320–341.
- [29] Yahaya R *et al.* (2016). Effect of fibre orientations on the mechanical properties of kenaf–aramid hybrid composites for spall-liner application. *Defence Technology*.12, 52–58.
- [30] Boukhoulida BF, Adda Bedia E and Madani K (2006). The effect of fibre orientation angle in composite materials on moisture absorption and material degradation after hygro-thermal ageing. *Composite Structures* .74, 406–418.
- [31] Abhilash AS *et al.* (2011). Micromechanics of diffusion-induced damage evolution in reinforced polymers. *Composites science and technology*. 71, 333–342.
- [32] Chilali A *et al.* (2016). Effect of geometric dimensions and fibre orientation on 3D moisture diffusion in flax fibre reinforced thermoplastic and thermosetting composites. *Composites Part A*, 95, 75–86.
- [33] Corinaldesi V and Nardinocchi A (2016). Influence of type of fibres on the properties of high performance cement-based composites *Construction and building materials*. 107, 321–331.
- [34] Sawa SK *et al.* (2014). Hybrid Composites Made from Jute/Coir Fibres: Water Absorption, Thickness Swelling, Density, Morphology, and Mechanical Properties. *Journal of Natural Fibres*, 11, 39–53.
- [35] Jain D, Mukherjee A and Kwatra N (2016). Numerical modelling of moisture diffusion in FRP with clustered microstructures, *Applied Mathematical modelling*, 40, 1873–1886.
- [36] Yu H and Zhou C (2018). Sandwich diffusion model for moisture absorption of flax/glass fibre reinforced hybrid composite, *Composite structures*, 188, 1–6.
- [37] ABAQUS/STANDARD Analysis User’s Manual, *Dassault Systems*, 2014, 2.
- [38] Askeland D, Fulay P and Wright W, Composites teamwork and synergy in materials. *The Science and Engineering of Materials (6th ed.)*, Cengage Learning, 2010, 665.
- [39] Halpin JC. *Primer on composite materials: analysis*. Lancaster, PA: CRC Press

Technomic, 1984, 43.

- [40] Hashin Z and Rosen BW (1964). The elastic moduli of fibre-reinforced materials. *Journal of Applied Mechanics*, 31, 223–232.
- [41] Wong TC and Broutman LJ (1985). Water in Epoxy Resins Part II. Diffusion Mechanism. *Polymer Engineering and Science*. 25, 9.
- [42] Pali R *et al.* (2012). Effect of laminate thickness on moisture diffusion of polymer matrix composites in artificial seawater ageing, *Material Science*, 6(3), 225–235.
- [43] Korkees F, Arnold C and Alston S (2018). An Investigation of the Long-Term Water Uptake Behavior and Mechanisms of Carbon Fiber /977-2 Epoxy Composites, *Polymer Engineering and Science*, (Online).

## **CURRICULUM VITAE**

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Mr. Sandeep Vats has completed his Bachelor in Technology degree in Mechanical Engineering from Punjab Technical University, Jalandhar, Punjab in 2016. In 2016, he joined Master in Engineering program in CAD/CAM at Thapar Institute of Engineering and Technology, Patiala with GATE scholarship. During ME- CAD/CAM, he worked on the topic ‘Hygro-Mechanical Behaviour of Fibre Matrix Laminates for Different Fibre Orientations’ for his Thesis work. Recently, his paper entitled ‘Moisture Diffusion along the Layered Fibre Matrix Composites with Different Fibre Orientations’ in ‘Materials Today: Proceedings’ got accepted.



## LIST OF PUBLICATIONS

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### *Accepted*

Vats S, Jain D and Bera TK (2017). Moisture Diffusion along the Layered Fibre Matrix Composites with Different Fibre Orientations, *Materials Today: Proceedings (Accepted)*, Elsevier

### *Communicated*

Vats S, Jain D, Bera TK and Mukherjee A.(2017). Three dimensional moisture diffusion micromechanics of multidirectional fibre matrix layups, *Composites Part A, Elsevier*



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