Development of open-source codes to predict the mechanical properties of unidirectional Carbon – Epoxy Composites

A PROJECT REPORT

Submitted in partial fulfilment of the requirements for the award of the degree

of

Master of Technology

by

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June 2021

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CERTIFICATE

This is to certify that the report entitled **Development of open-source codes to predict the mechanical properties of unidirectional Carbon – Epoxy Composites for Aerospace Applications**, submitted by **LOKESH** (T19061) in partial fulfilment of the requirements for the award of **MTech in Energy Engineering specialization in Materials** to the **School of Engineering**, **IIT Mandi** is an authentic record of research work carried out by him under my supervision and guidance. To the best of my knowledge, the work incorporated in this report has not been submitted elsewhere for the award of any degree.

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ACKNOWLEDGEMENT

Endeavours are never achieved alone; there are always several supportive hands. This report is a meticulous result of guidance of such people around me who have brought me all through the way. So, I would like to thank them all for their presence in my life in a small way. I am extremely fortunate to be involved in a challenging study of this kind. It has enriched my life, giving me an opportunity to work in a new area of computational predictions of mechanical properties of composites. This work enhanced my thinking abilities and understanding capability and after the completion of my work, I experienced a feeling of self-gratification.

I would first like to express my deep sense of gratitude to my guide Dr. Sunny Zafar who is an embodiment of knowledge, perseverance and tolerance for his excellent guidance, suggestions, extraordinary effort and support during my report work. Without his continual guidance this report would not have been materialized. One can never possibly wish for a better adviser and path maker in life. I would also like to express my sincere gratitude to Dr. Himanshu Pathak Assistant Professor and Mr. Rajeev Kumar Research scholar in CDML lab, IIT Mandi for his encouragement and illuminating feedbacks during my research work along with it. At last, I would like express my warm thankfulness to all other faculties who are directly and indirectly involved in report work.

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ABSTRACT

The study is dealing with the development of open-source codes using python and its libraries to predict the mechanical properties of unidirectional carbon epoxy laminates of different orientation sequences. Python codes were developed using classical laminated theory of failure for composites. With the help of codes, the complex stress distribution inside each layer of the laminate for various loading conditions can be found and understood. Further, different mechanical properties such as tensile modulus, shear modulus and flexural modulus can be also obtained for each principal axis of laminate.

Validation of codes are done through the computational and experimental results obtained through literature for different number of layers and orientation sequences of laminates.
Validation for the tensile modulus results is also done by fabricating three different samples of six layers using vacuum assisted microwave curing. Three orientation sequence that are used for the fabrication of samples are (0), (0/90), (45/-45). The samples were fabricated in the 1:1 weight percentage of matrix and reinforcement. To ensure the experimental values for tensile modulus, each experiment is done for five times. For the fabricated samples tensile modules, we get less than 15% error in predicted values.

A detailed summary about the continuously developing microwave fabrication method is given in the materials and methods section to understand the effect of microwaves on different materials. Some future recommendations are also given in the end to continue this work. At last, python codes are added for the reference in the end of the report.

Key words: unidirectional carbon epoxy composites, microwave curing, python codes, tensile strength, classical laminated theory.

CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

Composite materials are not new to mankind, they are present with us from more than 3000 years. In Egyptian times, people used bricks that were made from mud (matrix) and straw (reinforcement) to build their homes.[1] The word 'Composite' derived from a Latin word known as 'compositus' which means that putting different materials together to made something significant.[2] In general, we can say that composites are the materials having two or more phases and they should be physically distinct and mechanically separable. The advantage of using composites is that we get superior properties with respect to both the phases. Composites are also preferred as an important structural material because we can obtain the desirable properties which could not be achieved by any individual constituent alone. Composite have many advantages over traditional materials such as high strength to weight ratio, low probability of corrosion, directional strength tunability etc.

Composites are generally made up of two constituents, matrix and reinforcement. Some materials are stronger in fiber form in comparison with the bulk form. They provide excellent longitudinal strength but are weak in transverse direction. These fibers are used as reinforcements in the fabrication of composites. These fibers can be used in various forms such as long fibers, short fibers, woven mats, discrete fibers etc. To bind up these fibers together and improve their transverse strength, we use a matrix material which is distributed uniformly inside the composite. Polymers, ceramics, metals are all can be used as a matrix material depending upon the type of application and properties required. Matrix material helps to bind the fibers in a structural unit and helps in distributing uniform loads on fibers. In some cases, it provides ductility, toughness or electrical insulation for the composite. One thing to note is that the fiber and matrix must be chemically compatible so that undesirable chemical reactions do not take place. These reactions can be more challenging in high temperature application composite materials. Polymers are the most widely used matrix materials in modern composites. Polymer matrix materials can be categorised into thermosets (e.g., epoxy, phenols, polyesters) and thermoplastics (e.g., polyamides, PS, PEEK, PPS). Thermosets cannot be reused after curing.

They form a complex cross linked, 3D molecular structure which does not melt at high temperatures. On the other hand, thermoplastics are the reusable matrix materials, they get soft upon heating and hard upon cooling.

From centuries, composite became an alternative material to solve many technological problems. But from the development of polymer composites in 1960s, composites usage in industries became so high. It was the time when there was a huge competition in the world’s market to develop lightweight materials for aerospace industries and it became a common engineering material from then.[3] Fiber reinforced plastics (FRPs) are among the first materials which gain a huge demand in the last decades. It became so popular due to some of its distinct properties such as design flexibility, lightweight, durability and high corrosion resistance.[4] Glass fiber reinforced composites (GFRPs) were among the first structural composites. Glass, jute, polyester and other low modulus fibers were considered as basic composite materials due to their low cost and high availability, and they were used in wide range of applications such as in gears, bearings, railway components (door, seats, wagon etc.), house cells, chimneys, door panels, windows, furniture etc. [5]

With the growing need of material advancements to fulfil the demand of aerospace sector, Advance Composites materials arise as an alternative to various traditional metallic materials. Advance composites are made from high modulus fibers such as graphite, boron, aramid, silicon carbide etc. An example of their strength can be understood with the example of the stiffness in carbon fibers. The stiffness of carbon fibers is very high due to the C-C bonding strength of around 400 KJ/mol but it varies with the orientation of these aromatic rings in the direction of fiber.[6] Although they are not very cheap but their high cost can be justified with the improved performance of aircrafts.

1.2 Need of the Study

There are various factors that can influence the properties of composites like different polymer resin types (thermoplastic or thermosetting plastic), fabrication processes, curing time, heat and pressure for effective bonding, fiber types and orientations etc. The stress distribution inside a composite material is also quite complex even for a unidirectional loading. For the same material and composition of fiber and matrix, magnitude of stress can vary with orientation of fibers, thickness of lamina etc. As we know, that composites are orthotropic materials so we need 9 independent elastic constants to predict the behaviour. Although there are some well-established theories to predict the behaviour of composites but still, we can see the complexities of predicting the behaviour of composites numerically as well as experimentally due to the large set of influencing parameters. In these last decades, where computers become an essential part for various sectors due to their rapidly increased computational power, various technologies emerged that can forecast the mechanical properties of composites vary accurately. One such study was done by Qi Zhenchao et.al. to predict the mechanical properties of carbon composites using FEM and Machine Learning.[7] Now we can understand that the properties of composites are highly dependent on the orientation of fibers with the loading direction. For the same composite slab when loading in different directions, we can see a change in the properties of composite slab in different directions. So, it is obvious that we must have to know the best possible arrangement for the efficient use of composite materials.

1.3 Classical Laminated Theory

This theory helps us to predict the properties, failure of layers, effects of orientation and thickness of fibers. In this theory, Laminates are assumed as a homogeneous orthotropic sheet and their microstructural nature is been ignored. Then the laminated plates or shells theories can be easily incorporated for the analysis of such laminated composites. For an isotropic material, principal stresses can be calculated using the theories of elastic failures because the strength of the material is not change with the direction. But in case of orthotropic or anisotropic material, strength changes with direction, so above theories cannot be used.

Let's consider a unidirectional composite slab with continuous fibers for the modelling purpose. We have to consider an axis system. These directions are also known as principal material directions.

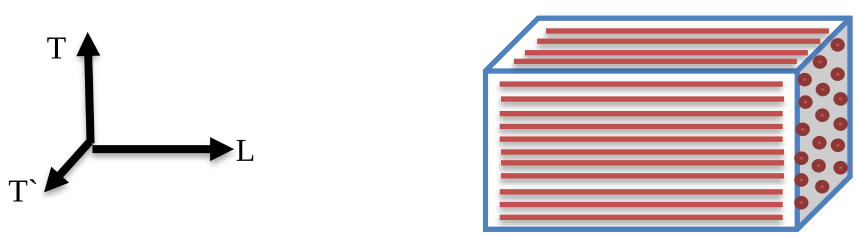


Figure 1.1: Schematic of a unidirectional laminate

L = Axis aligned to the length of the fibers (longitudinal axis)

T = Axis normal to L (transverse axis)

T` = Axis normal to L and T direction

Unidirectional composite generally considered as orthotropic in nature. It means the properties in any material plane (LT, TT`, LT`) remains same. In simple words we can say, within these planes, material properties are isotropic.

1.3.1 Strength Parameters of unidirectional composites

There are 5 parameters which defines the behaviour of unidirectional composites:

1) Longitudinal tensile strength (σ_{LU})
2) Longitudinal compressive strength (σ_{LU}`)
3) Transverse tensile strength (σ_{TU})
4) Transverse compressive strength (σ_{TU}`)
5) In plane shear strength (τ_{LTU})

After rigorous calculations, we are able to calculate the modulus of unidirectional composites in different directions.

1.3.2 Longitudinal Modulus (E_L)

Before calculation of longitudinal modulus, we need to know the following terms.

V_f = Volume fraction of fiber in the laminate

E_f = Young's modulus of fiber

E_m = Young's modulus of matrix

V_m = Volume fraction of matrix in the laminate

$$E_L = E_f V_f + E_m V_m$$

1.3.3 Transverse Modulus (E_T)

Transverse modulus can be best predicted using Halpin Tsai relationship:

$$\frac{E_T}{Em} = \frac{1 + \eta.\xi.V_f}{1 - \eta.V_f}$$

There are two parameters in this equation. These can be calculated differently for different fiber cross section areas.

- For circular cross section area of fibers, $\xi = 2$.
- For non-circular fibers, $\xi = 2 * a/b$

  (Note: Here a, b are length and breadth of fiber cross sectional area.)

η can be calculated using following equation:

$$\eta = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + \xi}$$

1.3.4 Shear Modulus (G_{LT})

Shear modulus can be best predicted using Halpin Tsai relationship:

$$\frac{G_{LT}}{G_m} = \frac{1 + \eta.\xi.V_f}{1 - \eta.V_f}$$

Here, G_m represents the shear modulus of matrix. There are two parameters in this equation. These can be calculated differently for different fiber cross section areas.

- For circular cross section area of fibers, $\xi = 1$
- For non-circular fibers, $\xi = a/b$

  (Note: Here a, b are length and breadth of fiber cross sectional area.)

η can be calculated using following equation:

$$\eta = \frac{\frac{G_f}{G_m} - 1}{\frac{G_f}{G_m} + \xi}$$

1.3.5 Poisson’s Ratio

There are two types of Poisson’s ratio according to the direction of loading.

a) Major Poisson’s Ratio(υ_{LT}): Composite loaded in L direction, while Poisson’s effect observed in T direction. Assume there is same strain in fiber, matrix and composite.

$$\upsilon_{LT} = \upsilon_m . V_m + \upsilon_f . V_f$$

b) Minor Poisson’s Ratio(υ_{TL}): Composite loaded in T direction, while Poisson’s effect observed in L direction.

$$\upsilon_{TL} = (E_m / E_L) * \upsilon_{LT}$$

1.3.6 Generalised Hooke's Law

Stress is defined as the external force acting on a unit area of the body. Stress acting at a point in a solid body can be represented with the help of stress components acting on that body. There are nine stress components that can act on the single face of an elemental cube. To define the stress, we need two subscripts (σ_{ij}), here *'i'* represents the direction of force and *'j'* represents the normal direction. Rotational equilibrium requires that $\sigma_{ij} = \sigma_{ji}$,, we assume that the rotational equilibrium is maintained due to rigid body. Now, we are left with six stress components, in which three components *(i = j) shows* the normal stresses and remaining shows shear stress components. External forces cause strains in the body. Strain can be defined as the ratio of change in dimension to the original dimension. In linear elastic region, the relationship between stress and strain in an isotropic material can be described using Hooke's law. Hooke's law in its most general form used for anisotropic materials is also known as generalized Hooke's law. For a fully anisotropic material, we require 81 constants to map the stress vector to strain vector. Consider that, i and j values can vary from 1 to 3. In tensor notation, we can write the equation as:

$$\boldsymbol{\sigma_{ij} = E_{ijkl} \, . \, \varepsilon_{kl}}$$

After consider some assumptions such as Newton's law of momentum equilibrium, law of geometry and strain energy considerations, we found that elasticity tensor become symmetric and now only 21 elastic constants are required to map the stress and strain tensor in anisotropic materials.

Special Case: Specially orthotropic material with applied in plane stress:

Characteristics of the material:

- Thin material
- Stresses in thickness direction are considered as zero.

It is the most important case because it resembles the composite single lamina which in T direction have the stresses assumed as zero. After simplification, we finally get a stiffness matrix [Q] which have 4 constants that can be obtained with the help of E_L, E_T, G_{LT}, υ_{LT}. Now we are in a position where we can obtain the stress strain relations for a lamina where material axis is aligned with the geometric directions of a composite slab.

$$\begin{bmatrix} \sigma 1 \\ \sigma 2 \\ \tau 12 \end{bmatrix} = \begin{bmatrix} Q11 & Q12 & 0 \\ Q12 & Q22 & 0 \\ 0 & 0 & Q66 \end{bmatrix} \begin{bmatrix} \varepsilon 1 \\ \varepsilon 2 \\ \gamma 12 \end{bmatrix}$$

This [Q] components matrix is known as Stiffness matrix. The components of [Q] matrix can be calculated as follows:

$Q11 = E_L / (1 - \upsilon_{LT} . \upsilon_{TL})$

$Q12 = (E_T . \upsilon_{LT}) / (1 - \upsilon_{LT} . \upsilon_{TL})$

$Q22 = E_T / (1 - \upsilon_{LT} . \upsilon_{TL})$

$Q66 = G_{LT}$

[Q] matrix is a very ideal case when fibers are oriented in the loading direction. But in a more general way, fibers can be oriented with any arbitrarily angle θ with the loading axis. In this case, we have to change the elements of [Q] matrix with the help of a transformation matrix which consists the sines and cosines of the angle θ.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q\overline{11} & \overline{Q12} & \overline{Q16} \\ \overline{Q12} & \overline{Q22} & \overline{Q26} \\ \overline{Q16} & \overline{Q26} & \overline{Q66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

[$\bar{Q}$] is a fully populated matrix. Here $\overline{Q16}$, $\overline{Q26}$ can be non-zero also. It implies that:

- Shear stress can generate extensional strains and vice versa.
- Extensional stress can generate shear strains and vice versa.

Note: At fundamental level [$\bar{Q}$] matrix also have 4 independent elastic constants. Each element of the matrix can be calculated as:

$\overline{Q11}$ = Q11.c^4 + Q22.s^4 + 2 (Q12 + 2Q66).s^2.c^2

$\overline{Q22}$ = Q11.s^4 + Q22.c^4 + 2 (Q12 + 2Q66).s^2.c^2

$\overline{Q12}$ = (Q11 + Q22 – 4Q66) .s^2.c^2 + Q12 (c^4 + s^4)

$\overline{Q66}$ = (Q11 + Q22 – 2Q12 – 2Q66) .s^2.c^2 + Q66 (c^4 + s^4)

$\overline{Q16}$ = (Q11 + Q12 – 2Q66).c^3.s – (Q22 – Q12 – 2Q66).c.s^3

$\overline{Q26}$ = (Q11 + Q12 – 2Q66).s^3.c – (Q22 – Q12 – 2Q66).s.c^3

Note: Here, c denotes cosθ and s denotes sinθ respectively.

1.3.7 Stiffness and failure in laminates

Laminates are the arrangement of different lamina with different or same orientation of fibers. Each layer of a laminate can has different properties or different orientation. There are certain assumptions that we have to consider:

1. The bond between two layers is of zero thickness. It means that the total laminate thickness is equal to the sum of thickness of each lamina.
2. Bond is assumed to be perfectly rigid. It implies that there is no shear strain present between each lamina.

1.3.7.1 Strain calculation in vector form

Assume that $\acute{\varepsilon}$ and $\acute{k}$ represents the strain and curvature of the mid plane. Z is the distance of each layer from the mid plane. The strains in each layer can be calculated in the vector form by the following matrix:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \acute{\varepsilon}_x \\ \acute{\varepsilon}_y \\ \acute{\varepsilon}_{xy} \end{bmatrix} + Z \begin{bmatrix} \acute{k}_x \\ \acute{k}_y \\ \acute{k}_{xy} \end{bmatrix}$$

By changing the values of Z, we can easily calculate the strains in different directions in each layer of the laminate.

1.3.7.2 Stress Calculation

Suppose we have 'n' number of layers and at a distance 'Z' there is a 'K' layers present. So according to the 'K' layer, first $[\bar{Q}]$ matrix for that layer has to calculate first. Then we use the basic relation of stress, strain and $[\bar{Q}]$ matrix. In equation form, we can write:

$$[\boldsymbol{\sigma}]_{xy} = [\bar{Q}]_K . \left[[\acute{\varepsilon}]_{xy} + Z.[\acute{k}]_{xy} \right]$$

1.3.7.3 Resultant Forces and Moments on Laminate

Consider:

h = total thickness of laminate

N_x = Force applied in 'x' direction per unit length

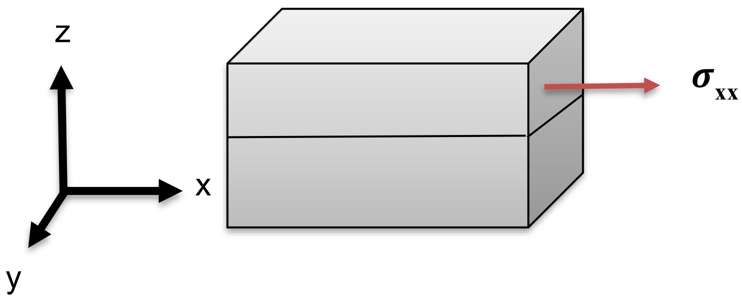


Figure 1.2: Laminate subjected to unidirectional loading

Resultant force in 'x' direction can be written as:

$$N_X = \int_{-h/2}^{h/2} \sigma_{XX}\, dz$$

Similar equations can be written for N_y and N_z. In matrix form, we can write them as:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz$$

On simplify further and incorporate the mid plane strains and curvatures, we finally get a matrix form which shows the relationship between mid-plane strains and curvatures with the resultant force and moment components. In matrix form, the equations can be written as:

$$[\mathbf{N}] = [\mathbf{A}].[\acute{\varepsilon}] + [\mathbf{B}].[\acute{k}]$$
$$[\mathbf{M}] = [\mathbf{B}].[\acute{\varepsilon}] + [\mathbf{D}].[\acute{k}]$$

Here,

[A] = Extensional Stiffness Matrix

[B] = Coupling Stiffness Matrix

[D] = Bending Stiffness Matrix

These force and moment equations depends upon the thickness of each layer and the orientation of fibers in each layer. At this point, it is easy to understand that variation in thickness and orientation of the composite layers can lead to significant changes on the resultant forces and moments.

1.3.8 Steps in predicting failure in composite laminates

1. Calculate [A], [B] and [D] matrix for the laminate sequence.
2. If [N] and [M] are known then calculate [ɛ́] and [ḱ] matrix.
3. Find σ_L, σ_T and τ_{LT} in each layer.
   - First calculate strains for each layer.
   - Transform them into L-T coordinates values.
   - Calculate σ_L, σ_T and τ_{LT}.
4. Use any failure theory (Tsai- Hill Criteria) to see if each layer is safe or not. If each layer is safe, then composite can withstand the external forces and moments. If some layers are failing then identify those layers.
5. Put $[\bar{Q}]$ = 0 for the failed layer.
6. Re compute [A], [B] and [D] matrix and repeat all the steps again and again until all the layers get failed.

1.4 Significance of the Study

This study will help the students and researchers to develop the open-source codes and modules to predict the behaviour of composite materials. This study can be helpful in reducing the time and cost of experiments and helps to reduce the dependency on high computing costly softwares. The codes are written in Python Programming language which is very easy to understand. To perform a quick analysis, these codes can be very helpful.

1.5 Conclusion

This work is about the development of open-source python codes using some python concepts such as Lists and User Defined Functions (UDF), python libraries (NumPy and pandas) and classical laminated theory for composite failures. Verification of codes is done through experimental and computational results and then the accuracy of the codes is predicted. Unidirectional Carbon-Epoxy composites has been made using vacuum assisted microwave curing for the experimentations. The codes can predict the best arrangement for the laminates and helps in finding the optimum values of mechanical properties according to the various loading conditions. Research findings can help us to understand the effect of orientation of fibers and number of layers on the strength of laminates. Further different corelations can be obtained on the basis of experiments to improve the prediction accuracy of the codes.

CHAPTER 2

LITERATURE REVIEW

Composite materials have so many parameters and by tuning these parameters, we get a wide range of properties in laminates. As we also previously discuss the challenges associated with the prediction of properties. To overcome this issue, and for getting the experimental values close to the predicted values, we have to choose the best parameters to fabricate a more defect free sample. Here, a review of currently available literature is done below to give some insights about the selected parameters in this work. The review is mainly based on the unidirectional carbon fiber composites and the effects of the orientation angle and thickness of fibers on the mechanical properties. Different composite fabrication methods are tried to compared, so that a suitable method can be decided for the work. This chapter contains the review of the existing research reports:

- On carbon fiber and carbon fiber reinforced composites
- On fabrication methods of polymer composites
- On effect of orientation angle in unidirectional laminates

2.1 On carbon fiber and carbon fiber reinforced composites

Now a days, carbon fiber and its composites are considered as a potential alternative to the metals in some specific industries such as aerospace and automobiles. When it comes to high strength to weight ratios (E.g. Fighter planes, luxury cars, rocket parts), Carbon fiber composites are way ahead of any materials in such applications. Carbon fiber composites along with boron, aramid, silicon carbide composites came under the category of advance composites. Although their costs are high but their costs can be justified by the improved performances in various applications. E. Fitzer et al. covers a whole-time journey of carbon fibers, he specifically covered the theoretical aspects, history, the present trends and future aspects of the carbon fibers. He compared the strength, stiffness, thermal expansion, fatigue, corrosion resistance of carbon fibers to steel and aluminium and found that carbon fiber is superior in all these properties in comparison with steel and aluminium. He also compared glass, polyaramids and carbon reinforced polymer composites in terms of density, strength and elastic modulus and concluded that CFRCs have the superior quality in all those composites.[6]

B. Muralidhara et al. studied the effect of fiber architecture on the properties of carbon-epoxy composites. He used three different fiber architectures T300CF, T700CF, T800CF and perform the experiments on these 60:40 weight ratio composites. After experimentations he concluded that the T800CF showed higher inter laminar shear strength and hardness then others. The impact strength was found to be highest in T700CF composites. Further, he shows the importance of weaves structure on the composite's performance.[8]

Sudhin A U et al. done a comparative study between the carbon fiber reinforced thermoplastics and thermosetting plastics properties for aerospace applications. He used polyether ketone (PK) and epoxy (EP) as two different types of matrix and used carbon fiber (CF) as reinforcement. After conducting the experiments, he concluded that the PK-CF composites having high tensile modulus, stress intensity factor and glass transition temperatures in comparison with EP-CF composites.[9]

C.Soutis et al. proposed that the use of carbon fiber can be increased to a significant amount in aerospace sector, He build a model to define and analyze the feasibility of using carbon composites in an aircraft. He analyzed that 40% weight can be saved by using carbon fiber composites instead of light metal alloys for secondary structure, while in the case of primary structures such as wings and fuselages 20% weight reduction can be achieved. [10]

Sufang Tang et al. reviewed on design and preparation of carbon fiber reinforced ceramic composites for ultra-high temperature aerospace applications. He summarized the mechanical properties of various different high temperature composites obtained through various fabrication methods. He concluded that the C/C–SiC–UHTC and C/UHTC composites can be used in high temperature applications such as engine propulsions and hypersonic vehicles due to their good oxidation, ablation and thermal shock resistance, high strength and fracture toughness. He also summarized the physical and chemical properties of various carbon reinforced composites. [11]

2.2 On fabrication methods of polymer composites

Fabrication method and the curing plays a very important role in determining the properties of composite materials. Two samples prepared through two different fabrication methods can vary hugely in their mechanical properties. The table given below can summarize various fabrication methods and their effects on the properties:

Table 2.1: Review of different fabrication methods of polymer composites

S/no	Author	Orientation sequence	Fabrication Method	Results
1.	Rajeev et al. [12]	(0/90), $(0,90)_2$, (45/-45), $(45/-45)_2$, $(0/90)_3$, $(45/-45)_3$ Carbon-epoxy	vacuum-assisted resin infusion microwave curing	Elastic and shear modulus is higher in (45/-45) orientation while the fracture toughness is higher in (0/90).
2.	Hossein Rahmani et al. [13]	(0, 35, 45, and 90) – 3 and 5 ply Laminates Carbon-epoxy	Hand layup and vacuum bagging	(0, –35, 0, +35, 0) orientation showed highest Tensile modulus.
3.	Narendra Kumar Jha et al. [14]	[0,45,-45,60,90]s, [0,90,0,90,0]s, [0,15,30,45,60]s, [90,0,90,0,90]s, [90,-90,90,-90,90]s, [-90,0,-90,0,-90]s, [0,-90,0,-90,0]s, [0,0,0,0,0]s, [0,45,90,-45,-90]s Glass Epoxy	RVE and Python codes	Max tensile strength (4974 MPa) – (0,0,0,0,0)s Max Von mises stress = 12952 MPa (90,-90,90,-90,90)s
4.	M. Sharma et al. [15]	(0°,15°,30°,45°,60°,75° and 90°) carbon-polyetherimide	Hand layup and Compression Moulding	Max young's modulus (0°) = 130.24 GPa Max shear modulus (60°) = 863.46 MPa Max ILSS (0°) = 27.17 MPa
5.	Hossein Rahmani et al. [16]	(0,90,0), (0,35,0),(90,35,90) – 3 ply (0,-35,0,+35,0), (+35,-35,0,+35,-35) -5 ply And same orientation with 11 and 23 plies Carbon-Epoxy	Hand Layup	(0°,90°,0°) followed by (0°,-35°,0°,+35°,0°) showed the highest tensile strength compared to other studied composites,
6.	H.W. Wang et al. [17]	(0°,15°,30°,45°,60°,75° and 90°) Glass-epoxy	water jet technology and vacuum curing	0° orientation shows max tensile strength. Young's modulus showed a U shape curve between 0° to 90° orientations. Fiber content and young's modulus showed a linear relationship.
7.	Kakur Naresh et al. [18]	(0), (45), (90) – 6 layers (45/-45/45)s and (±45/0/90)s Carbon-Epoxy	Hand layup followed by Compression Molding	0° orientation showed superior tensile properties. But (45/-45/45)s and (45/-45/0/90)s can also be taken into consideration.

Although we know that there are several fabrication methods are available, but for this study we use Vacuum assisted microwave curing technique to fabricate the unidirectional CFRCs. Microwaves are the electromagnetic waves of frequencies between 1 GHz to 1000GHz with a wavelength range of approximately 30 cm. There are various advantages of microwave heating over conventional techniques such as microwave heating provides uniform and rapid heating, it also provides selective heating which in turns helps to reduce the defects, it is a eco-friendly method that can be used on a variety of substrates, the processing cost and time is very less, so it is a good economical alternative to other traditional fabrication methods. Some literature is provided below to understand the benefits of using microwave heating over traditional methods.

2.2.1 Effect of Microwave heating on mechanical properties of CFRCs

D.A Papagyris.et al. observed 50% reduction in curing time of CFRCs and a 9% increase in inter laminar shear strength (ILSS) by resin transfer molding microwave heating over conventional heating. [19]

Kimiyasu Sato et al. found that Microwave curing of CFRCs resulted in remarkably larger flexural failure strain values. It seems that the local thermal transfer from CFs to the matrix due to microwave irradiation modified the physio-chemical linking at the CF-matrix interface. [20]

Xuehong Xu et al. observed A 39% cure cycle time reduction and a 22% compressive strength increment were achieved for the carbon-epoxy composites manufactured with vacuum bagging microwave radiation in compare to thermal curing. [21]

Radha Raman Mishra et al. described about the fundamentals of microwave processing, heating mechanisms in different type of materials and different challenges in processing of advance materials. [22]

Xiaoping Chen et al. showed that the tensile strength and shear strength values of the CFRCs specimens cured by high-pressure microwave was about 9.2 % and 4.2% higher than the average values of specimens fabricated by autoclave curing. [23]

Shimamoto et al. cconcluded that the curing rate of microwave-irradiated carbon-epoxy composites (CFEC) was 15 times faster as compared to conventional heating. The mechanical properties of CFEC cured by microwave irradiation for 20 min at 120 °C were similar as compared to the conventional oven for 300 min at 120 °C. [24]

Nanya Li Daisuke et al. observed that microwave curing reduces the induced residual strains and total curing time was reduced by 45%, better tensile modulus and flexural strength values were obtained for CFRP specimens by microwave curing in comparison with autoclave curing. [25]

Nishant Verma, Rajeev Kumar et al. Describe about the benefit of using vacuum in composite fabrication to enhance the mechanical properties. They observe a 116% increment in tensile strength, 45% increase in hardness and reduction in curing time by using vacuum assisted microwave curing. [26]

2.3 On effect of orientation angle in unidirectional laminates

As we have seen in table that the orientation angle plays a huge role in determining the mechanical properties of composites. So, it becomes necessary to find out the optimum configurations to certain specific properties. For example, in case of unidirectional laminates, the maximum tensile strength values are found along the major principal axis (‘L’) and minimum values are found along the minor principal axis (‘T’). A literature is summarized below to see the effects of orientation angles on various properties of laminates.

A comprehensively investigation on the mechanical and fracture behavior of unidirectional carbon woven fabric reinforced epoxy composite fabricated using vacuum-assisted resin infusion microwave curing technique for different orientations and number of layers is done by Rajeev et al. using experimental and computational techniques, he observed that the elastic and shear modulus is higher in (45/-45) orientation cross ply laminates while the fracture toughness is higher in (0/90) orientation laminates. [27]

The effects of fiber orientations (0, 35, 45, and 90), resin types, and number of laminates on mechanical properties of laminated carbon – epoxy composites have been investigated by Hossein Rahmani et al., he observed that the mechanical properties such as tensile, flexural and impact strength are mainly depending upon the orientation of fibers followed by the number of layers and the order of influencing parameters is fiber orientations > number of laminates > resin type. Later he found that the superior tensile and flexural strength was observed in the (35/-35) orientation laminates. [28]

Narendra Kumar Jha et al. used 10 ply glass/epoxy laminates of different orientations and analyzed the strength and displacements for those laminates using RVE and python codes. He observed that the unidirectional laminates showed better mechanical properties compared with other laminates and maximum mises stresses were found in case of angle ply laminates.[9]H.W. Wang studied the effect of orientation angle using numerical, analytical and experimental methods to see the variation in young's modulus of glass fiber reinforced composites with the help of basic theory of elastic mechanics.[14]

M. Sharma et al. studied the effect of orientation angle of long fibers carbon- polyetherimide composites on their mechanical and tribological properties. He used the orientation angles as (0◦,15◦,30◦,45◦,60◦,75◦ and 90◦) with the loading axis. He observed that properties get deteriorated with the increment of orientation angle and 0◦ orientation shows the superior modulus and strength.[15]

S. Ekşi et al. compared the mechanical properties of carbon, aramid and glass epoxy composites. They observed from the test results, that the unidirectional carbon fiber shows better properties in comparison with glass fibers. 0◦-orientation unidirectional fibers showed better mechanical properties than the 90◦-orientation fibers. When the woven types of fibers are considered, aramid-fiber-reinforced composites showed the superior mechanical properties.[28]

V.L. Reis et al. Obtained max tensile modulus of 51 GPa at 2 bar pressure and 0º orientation and get highest strain rates at 45º where the failure mode changed from longitudinal cracking to delamination bucking by using resin infusion technique which is cured in two steps. First it was cured for 24 hr at 25ºC and then it cured for 4 hr at 100ºC. [29]

2.4 Research findings from Literature

- Uniform heating from microwave curing.
- Mechanical properties increased by using microwave curing.
- Vacuum helps in reducing porosity and results in better adhesion between fiber and matrix materials.
- Reduction in processing time of composites by using microwave.

CHAPTER 3
MATERIALS AND METHODS

This chapter comprises of the materials and methods related to this current study. This chapter highlights the background thinking behind this work, some physical and mechanical properties associated with the materials, detailed discussion of the fabrication method of this work.

3.1 Materials

We try to fabricate different laminates in this work. In material section, we try to emphasize on the materials used to make the samples.

3.1.1. Matrix Material

The matrix material in any composite fabrication is the one which is continuous and is present in greater quantities within the sample. Matrix material is generally used to bind up the fibers together, it also protects the fibers from any mechanical and environmental damage. Matrix phase also helps in distribute the load uniformly on the fibers. According to the used cases, matrix materials divided into three types; metallic, polymers and ceramics. Although the most common material is the polymers because of their low costs, chemical stability and ease in processing. There are two categories within the polymeric matrix materials, they are known as thermoplastics and thermosets. Thermoplastics are a more ductile and tougher phase and thermosets due to the cross-linking properties are less ductile compared to thermoplastics. Thermoplastics are reusable they gain their initial stage and can be reshaped with the help of heat and pressure but the cross-linking property in thermosets would not allow them to go under change and hence they can’t be reused for reshaped. Despite these disadvantages, thermosets have an upper edge over thermoplastics when we compared the creep resistance and operating temperatures. Some examples of the thermoplastics are nylons, polystyrene, acrylics and polyethylene. The most common matrix materials in thermosets are epoxy, polyesters, phenolics and polyamides. The most commonly used thermoset matrix material is the epoxy resin. Epoxy has several advantages which makes it a general-purpose matrix material such as good corrosion and chemical resistance, good thermal, electrical and mechanical properties, good adhesion with different kinds of substrates, less shrinkage upon curing and ability to process in a variety of conditions. [30]

For the fabrication of the samples in this present study, an industry grade epoxy is used to bind up the different stacking sequences of unidirectional carbon fiber which is used as the reinforcement material in this study.

3.1.2 Reinforcement Material

In general, the phase which is present in the less amount and discontinuous in the composites are known as the reinforcement phase. It is usually harder and stronger than the continuous phase and is responsible for carrying most of the loads in practice. Reinforcement phases can be used either in the fiber form, fillers or in the form of suspended particulates. Fibers as reinforcement is most commonly used because composites are easy to manufacture and we have more control over the properties. Fibers can be obtained from various natural resources as well as can be made from artificial methods also. Natural fibers are a whole lot of different field in composites but for this present study, we are going to study about only the man-made fibers. The most common manmade fibers are carbon, glass, aramid and boron. Carbon fibers are most suited when we need high strength to weight ratios, high chemical and temperature resistance and high tensile strengths. Carbon fibers are mainly classified by their precursors and mainly divided as PAN based carbon fiber, Pitch based carbon fiber and rayon-based carbon fiber. The most commonly used category of fibers is the PAN based fibers because PAN process is simple and more economical due to the high carbon fields. The properties of different precursors are given in the table 3.1.

Table 3.1: Axial tensile properties of carbon fibers [31]

Precursor	Tensile Strength (GPa)	Tensile Modulus (GPa)	Elongation at Break (%)
PAN	2.5 – 7.0	250 - 400	0.6 – 2.5
Mesophase pitch	1.5 – 3.5	200 – 800	0.3 – 0.9
Rayon	~ 1.0	~ 50	~ 2.5

Carbon fibers can be used as unidirectional fibers and can also be used as a woven mat based on the applications. For the purpose of this study unidirectional carbon fibers of GSM 400 are used. The purpose of using the unidirectional fibers is to see the effect of orientation on the mechanical properties of laminates and it becomes also easy to predict the same values through computations.

3.2 Sample Fabrication

Samples of different stacking sequences are prepared to analyze the effect of orientation on the laminate's mechanical properties. The number of layers is kept constant. A total of 6 layers of carbon fibers are used to fabricate each sample. The samples are fabricated in a 50:50 weight percentage ratio of matrix and reinforcement. Epoxy is used as the matrix material and unidirectional carbon fibers are used as reinforcement. Vacuum assisted resin transfer molding is used to fabricate the sample and microwave curing is used to cure the samples. Three types of orientation ply will be used to fabricate CFRPs through vacuum assisted microwave curing:

- 6 ply cross laminates $(0 – 90)_3$
- 6 ply unidirectional laminates (0^o orientation)
- 6 ply angle laminates $(-45/45)_3$

The reason of selecting these three types of samples is that we want to analyze the every simple to complex stress distributions inside each layer of laminates. We select cross ply and angle ply laminates to analyze the normal and shear stresses inside layers respectively. We select a unidirectional laminate to find the optimum values of longitudinal and transverse modulus.

The material properties are summarized in the table 3.2:

Table 3.2: Properties of the materials used in the fabrication

Material	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Shear Modulus (GPa)**	**Poisson's Ratio**
Epoxy	42	3	1.1	0.28
Carbon Fiber	4000	240	15	0.3

To fabricate these samples, first we put a peel ply over a poly tetrafluoroethene (PTFE) mould. After that we put the layers according to their stacking sequences and then again cover it with the help of a peel ply. Then we apply a perforated film and on top of that we put a breather to absorb the extra resin. Then we fix two resin inlet connectors (RIC) for the flow of resin. One connector is connected to a suction pump to create vacuum inside the sample and other is connected to the container of resin. As we know, carbon fiber are highly conductive in nature, so to prevent arcing in the microwave, we used aluminium tape over some extra parts of the sample which we do not want to expose to microwave such as edges and corners of the sample. And then finally we apply a vacuum bagging film to maintain the vacuum inside the sample during fabrication. After that we put the samples in the microwave for curing.

3.3 Methods

There are different methods to fabricate the composites such as hand layup, compression moulding, resin transfer moulding, vacuum assisted resin transfer mouldings etc. The fabrication methods mainly depend on the characteristics of matrix and reinforcement materials, the shape and size of the samples and the end use and level of detailing required in the samples. To compensate the extensively growing needs of composites in various sectors such as aerospace, automobiles and nuclear reactors, we required some efficient, economical, time saving and environment friendly methods for the fabrication of composite materials. One such method known as vacuum assisted microwave curing is used in this study to fabricate the samples. This is a continuously developing fabrication method and researchers are continuously trying to understand the phenomena of microwave interaction with various materials.

3.3.1 Vacuum Assisted Microwave Curing

Heating of materials from microwaves are not new to us, we see people used microwave energy to cook their foods on the daily basis. But microwaves behave differently with different kinds of materials and only certain kinds of materials can be heated through microwaves. But luckily carbon fibers are a huge conductor of microwave which allow us the fabrication of our samples. Microwave heating is very different from the conventional heating methods. In conventional heating, first surface gets heated and then heat transferred to the bulk of the material. But, on the other hand in microwave heating, heat is generated due to the rapidly oscillating electromagnetic fields. The molecules inside the materials starts moving with respect to the oscillating waves and this rapidly changing electromagnetic waves increase the momentum in the bulk of the material. Now various interaction forces such as inertial, frictional, molecular forces try to resist these frequent changes of material dipoles which increase the molecular kinetic energy and results in a uniform volumetric heating inside the material.

The two main parameter for material interaction with microwaves are the dielectric loss factor and magnetic properties of the material. As these factors are responsible for the electric and magnetic field interactions with the materials. There are mainly three categories of materials according to microwave interaction.

Category 1: are those material in which the decrease in electric and magnetic field strength is almost zero. They are also known as low loss insulator materials or Transparent materials. E.g., Teflon, Quartz etc.

Category 2: are those materials in which the electric and magnetic field strengths decreased with increase of the dielectric loss factor. They are known as the high loss insulators or Absorber materials. E.g., water, SiC etc.

Category 3: are those materials in which there is a negligible decrease in electric and magnetic field strengths up to some few micrometres of thickness of materials. They are also known as the no loss insulators or opaque materials. All bulk metals came under this category.

Mixed Absorbers: These are the kind of materials which have more than one phase. Here one phase act as a high loss insulator and other is a comparatively low loss insulator. In this type of materials localized energy conversion takes place. E.g., PMC, CMC, MMC etc.

In non-magnetic materials, the heating is mainly depending on the dipolar losses and conduction losses while in case of magnetic materials hysteresis loss and eddy current loss dominates the heating. Composites heating mainly depends on dipole structure, frequency of microwaves, temperature and properties of matrix and reinforcement materials. In composites the localized selective heating mainly dominates by the high dielectric loss factor material. In the case of low conductivity fibers such as glass, aramid and some natural fibers, heating mainly dominates by the matrix materials. While on the other hand for high conductivity fibers heating mainly depends upon the fiber phase. As we use a thermosetting matrix, here the cross linking also affects the microwave energy absorption. Due to the cross-linking the internal structure becomes more complex which increase the viscosity of the matrix which restrict the change in dipole orientations in an oscillatory electric field. This, at higher cross-linking, microwave absorption gets reduced. [22]

Now we see the complexities in the material interaction with microwaves, in our samples the heating is mainly dominated by the carbon fibers. Here we put our samples in microwave irradiation of 2.2 KW and in 540 W and our samples get cured in 2 minutes and in 10 minutes respectively.

3.4 Testing of Mechanical Properties

3.4.1 Tensile Strength

The mechanical testing deals with many types of properties such as tensile strength, compressive strength, flexural strength and various modulus values. For all these kinds of testing we use a Universal testing machine (UTM). For the purpose of our study, we use this machine to find out the tensile strength and modulus values of various samples and further those results are match with the predicted results of python codes and then accuracy of the codes is verified. In tensile test the sample get stretched by some amount of load up to the fracture of the material. Then a graph between the stress and strain values is generated by the computer which helps us in finding various points in a stress-strain curve as well as the tensile modulus values, ductility, resilience, and toughness properties. For our study, the samples are tested on a UTM which follows the ASTM standards. The standard sample dimensions are given below:

- Length of specimen: 150 mm
- Width of specimen: 10 mm
- Gauge length: 80 mm.
- Grip length: 35 mm

The test results are generated by the computer and are shown in results and discussions later.

CHAPTER 4
RESULTS AND DISCUSSIONS

Computational results for various loading conditions and mechanical properties are found out with the help of open-source codes and then those results are validated through Ansys results as well as through experimental results from samples and from presently available literature. Uncertainty in experimental results is also take care by repeatability of experiments. Finally, codes validation accuracy is calculated for computational and experimental results.

4.1 Codes Validation of computational results for uniaxial loading

Problem Statement: There is an antisymmetric angle ply laminate of unidirectional graphite-epoxy laminae of thickness 0.25mm each with orientation angle sequence as (-45/+45/-45/+45). The Engineering constant values are: E_L = 138 GPa, E_T = 9 GPa, G_{LT} = 6.9 GPa, ν_{LT} = 0.3, ν_{TL} = 0.0196. This laminate is subjected to single uniaxial force per unit length of 50 MPa-mm. [32]

```
---------------------------- Stress State in XY plane -

                           Sigma_X    Sigma_Y     Tau_XY
Location
layer[1] top:         36.037676 -13.962324  -6.537914
layer[1] bottom:      45.345892  -4.654108 -16.344784
layer[2] top:         63.962324  13.962324  35.958525
layer[2] bottom:      54.654108   4.654108  26.151654
layer[3] top:         54.654108   4.654108 -26.151654
layer[3] bottom:      63.962324  13.962324 -35.958525
layer[4] top:         45.345892  -4.654108  16.344784
layer[4] bottom:      36.037676 -13.962324   6.537914
-------------------------------------------------------
```

Location	σ_x (MPa)	σ_y (MPa)	τ_{xy} (MPa)
#1 Top	37.3	−12.7	−6.2
#1 Bottom	45.8	−4.2	−15.5
#2 Top	62.7	12.7	34.0
#2 Bottom	54.2	4.2	24.7
#3 Top	54.2	4.2	−24.7
#3 Bottom	62.7	12.7	−34.0
#4 Top	45.8	−4.2	15.5
#4 Bottom	37.3	−12.7	6.2

Figure 4.1: Stress distribution values from computations and their validation

In Figure 4.1. the stress distributions inside the layers of that angle ply laminate are shown. Here, we can observe the complexities in the stress distributions of any laminate. The RHS values are calculated using Ansys while LHS values are calculated using the codes. Here we can see that results are very similar to each other. Accuracy of these codes is calculated using the mean square error between the actual and predicted values for each stress direction.

4.1.1 Codes Accuracy in Uniaxial loading

First of all, the percentage errors are calculated for each individual layer and then to see the overall error in the stress values inside the laminate, the mean square error (MSE) is used.

Table 4.1: Accuracy of codes in uniaxial loading case in 'L' direction

Sequence	Stress in 'L' direction			
	python results	Ansys result	Difference	% error
layer 1 top	36.037676	37.3	-1.262324	-3.5%
layer 1 bottom	45.345892	45.8	-0.454108	-1.0%
layer 2 top	63.962324	62.7	1.262324	2.0%
layer 2 bottom	54.654108	54.2	0.454108	0.8%
layer 3 top	54.654108	54.2	0.454108	0.8%
layer 3 bottom	63.962324	62.7	1.262324	2.0%
layer 4 top	45.345892	45.8	-0.454108	-1.0%
layer 4 bottom	36.037676	37.3	-1.262324	-3.5%

Table 4.2: Accuracy of codes in uniaxial loading case in 'T' direction

Sequence	Stress in 'T' direction			
	python results	Ansys result	Difference	% error
layer 1 top	-13.962324	-12.7	-1.262324	9.0%
layer 1 bottom	-4.654108	-4.2	-0.454108	9.8%
layer 2 top	13.962324	12.7	1.262324	9.0%
layer 2 bottom	4.654108	4.2	0.454108	9.8%
layer 3 top	4.654108	4.2	0.454108	9.8%
layer 3 bottom	13.962324	12.7	1.262324	9.0%
layer 4 top	-4.654108	-4.2	-0.454108	9.8%
layer 4 bottom	-13.962324	-12.7	-1.262324	9.0%

Table 4.3: Accuracy of codes in uniaxial loading case in 'LT' direction

Sequence	Stress in 'LT' direction			
	python results	Ansys result	Difference	% error
layer 1 top	-6.537914	-6.2	-0.337914	5.2%
layer 1 bottom	-16.344784	-15.5	-0.844784	5.2%
layer 2 top	35.958525	34	1.958525	5.4%
layer 2 bottom	26.151654	24.7	1.451654	5.6%
layer 3 top	-26.151654	-24.7	-1.451654	5.6%
layer 3 bottom	-35.958525	-34	-1.958525	5.4%
layer 4 top	16.344784	15.5	0.844784	5.2%
layer 4 bottom	6.537914	6.2	0.337914	5.2%

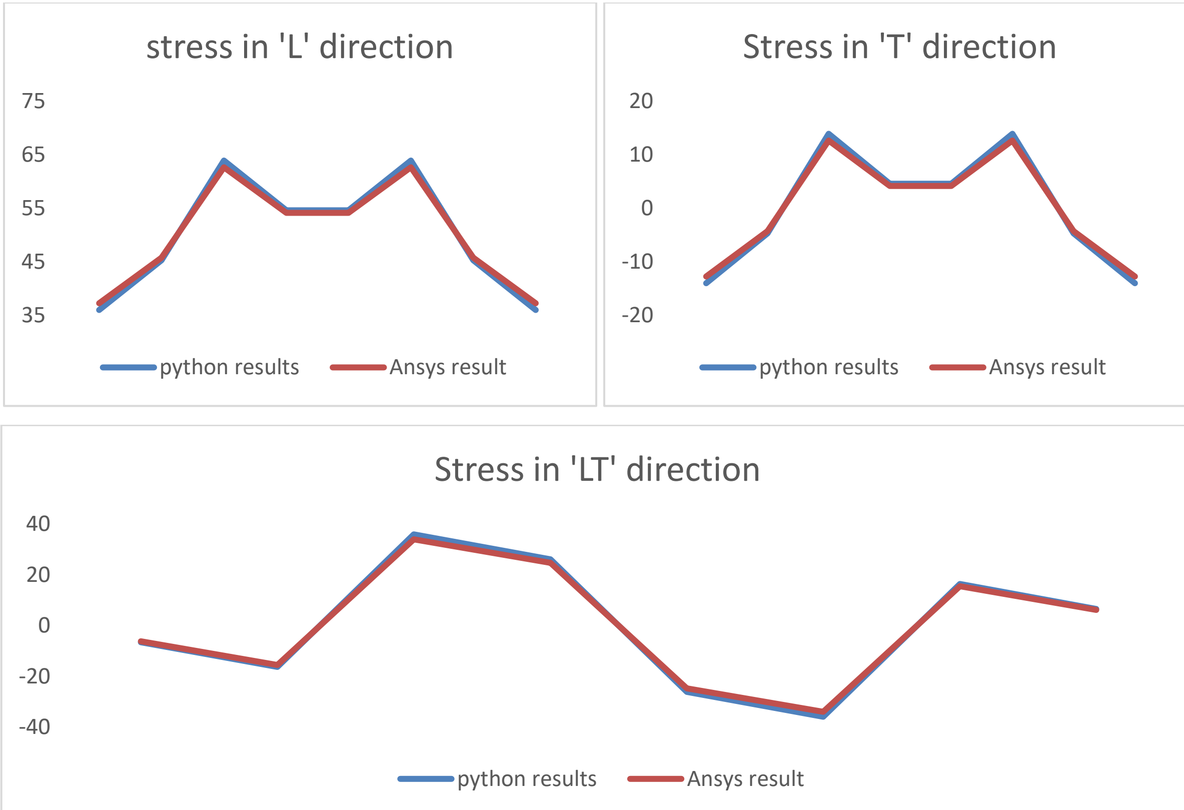


Figure 4.2: Codes Validation Accuracy for uniaxial loading

4.2 Codes Validation of computational results for biaxial loading

Problem Statement: This is a antisymmetric angle ply laminate of unidirectional graphite- epoxy laminae of thickness 5mm each with orientation angle sequence as (0/30/-45). The Engineering constant values are: E_L = 181 GPa, E_T = 10.3 GPa, G_{LT} = 7.17 GPa, V_{LT} = 0.28, V_{TL} = 0.016. This laminate is subjected to biaxial force per unit length of 1000 MPa-mm. [33]

Table 4.4: Accuracy of codes in biaxial loading case in 'L' direction

Sequence	**Stress in 'L' direction**			
	python results	**Ansys result**	**Difference**	**% error**
layer 1 top	31050.1	33513.2	-2463.1	-7.9%
layer 1 bottom	58070.5	55767	2303.5	4.0%
layer 2 top	61127.04	69297.1	-8170.06	-13.4%
layer 2 bottom	154805.34	143363	11442.34	7.4%
layer 3 top	125302.03	123568	1734.03	1.4%
layer 3 bottom	-30355.03	-25468.6	-4886.43	16.1%

Table 4.5: Accuracy of codes in biaxial loading case in 'T' direction

Sequence	Stress in 'T' direction			
	python results	Ansys result	Difference	% error
layer 1 top	61087.17	61875.4	-788.23	-1.3%
layer 1 bottom	45385.17	45312.1	73.07	0.2%
layer 2 top	70961.61	73914.1	-2952.49	-4.2%
layer 2 bottom	85858.53	81021.5	4837.03	5.6%
layer 3 top	158656.7	156279	2377.7	1.5%
layer 3 bottom	-21949.2	-18402	-3547.2	16.2%

Table 4.6: Accuracy of codes in biaxial loading case in 'LT' direction

Sequence	Stress in 'LT' direction			
	python results	Ansys result	Difference	% error
layer 1 top	-29657.64	-27503	-2154.64	7.3%
layer 1 bottom	-13605.98	-12800	-805.98	5.9%
layer 2 top	33609.76	33807.6	-197.84	-0.6%
layer 2 bottom	93193.92	84256	8937.92	9.6%
layer 3 top	-124781.41	-118672	-6109.41	4.9%
layer 3 bottom	41241.35	40912.6	328.75	0.8%

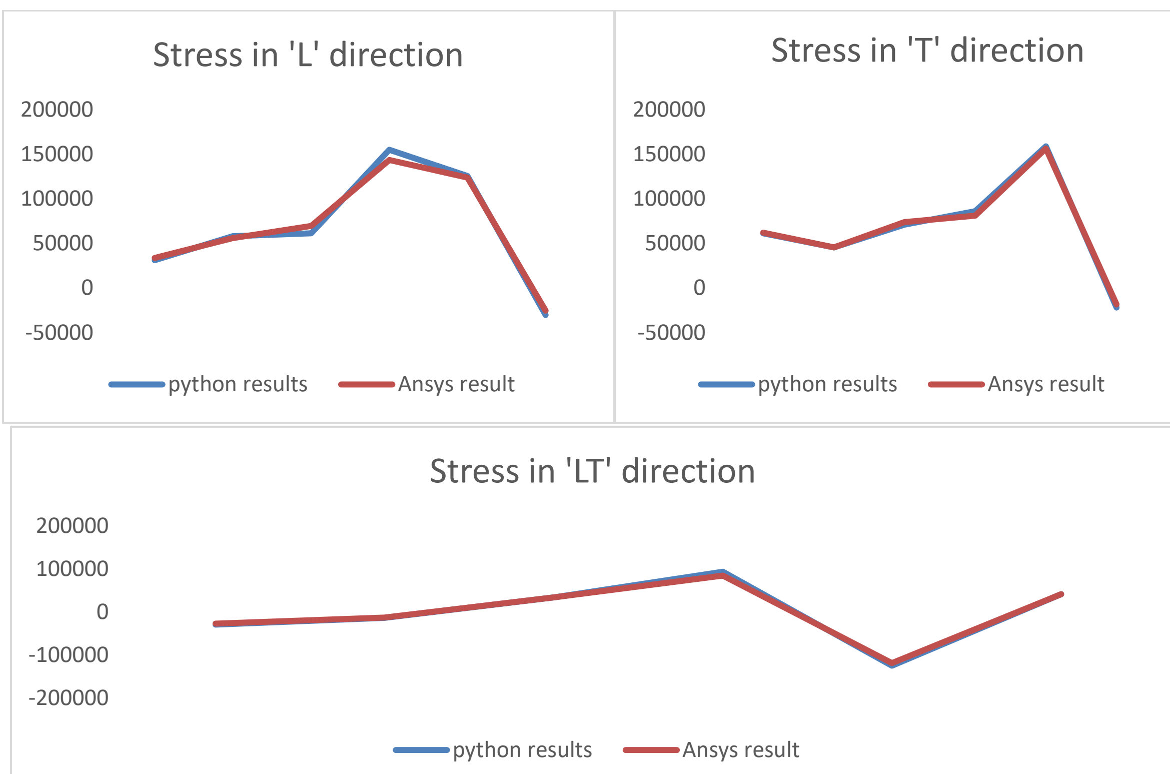


Figure 4.3: Codes Validation Accuracy for biaxial loading

4.3 Codes Validation from Experimental values of Literature

4.3.1 Codes Validation for tensile modulus

To validate the results of tensile modulus, we use the experimental values of tensile modulus from the literature for different orientation sequence and try to compare the results. Although we know, that experimental results depend on many factors such as fabrication method, curing time, temperature and pressure, manual mishandling of materials during manufacturing etc. But still, we try to see the correlation between the actual and predicted values. The data is summarized in the table below:

Table 4.7: Codes validation for tensile modulus from literature [16, 18]

Tensile Modulus			
Samples	**Experimental (GPa)**	**Theoretical (GPa)**	**% error**
(0^o) - 6 layers	109.88	120.78	-10%
(45^o) - 6 layers	10.4	11.198	-8%
(45/-45/45)s	11	12.46	-13%
(+45/-45/0/90)s	40.88	41.5	-2%
(90^o) - 6 layers	7	11.29	-61%
(0, 90 , 0)	65	78	-20%
(0,35,0)	60	65	-8%
(90, 45, 90)	9.5	14.72	-55%
(0, 35, 0, 35, 0)	81.6	102	-25%
(0, -35, 0, 35,- 35)	47	53.7	-14%
(0, -35, 0, -35, 35)	46.5	53.7	-15%
(0, 90, 0, 90, 0)	64.8	93.03	-44%

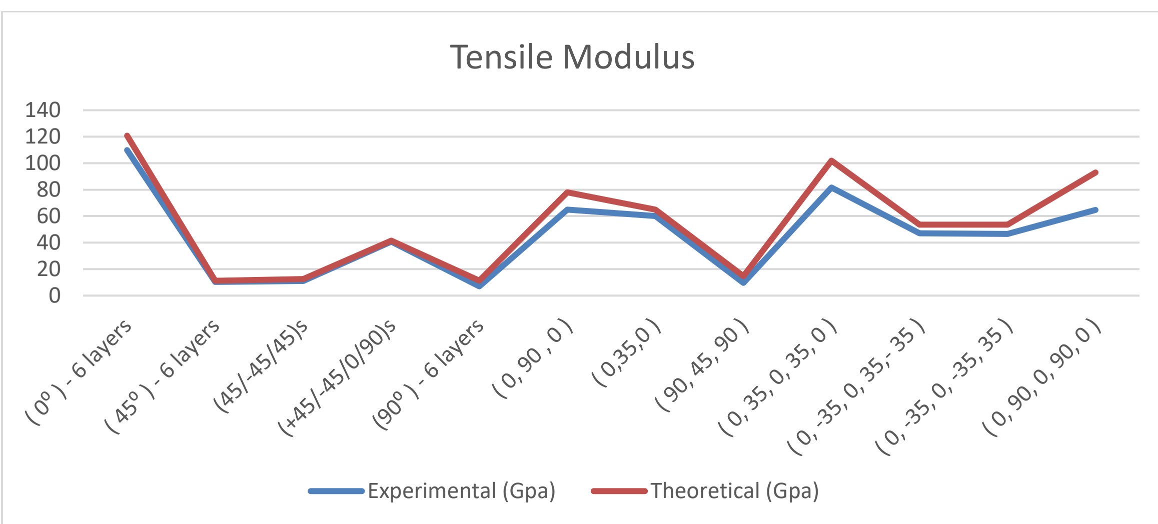
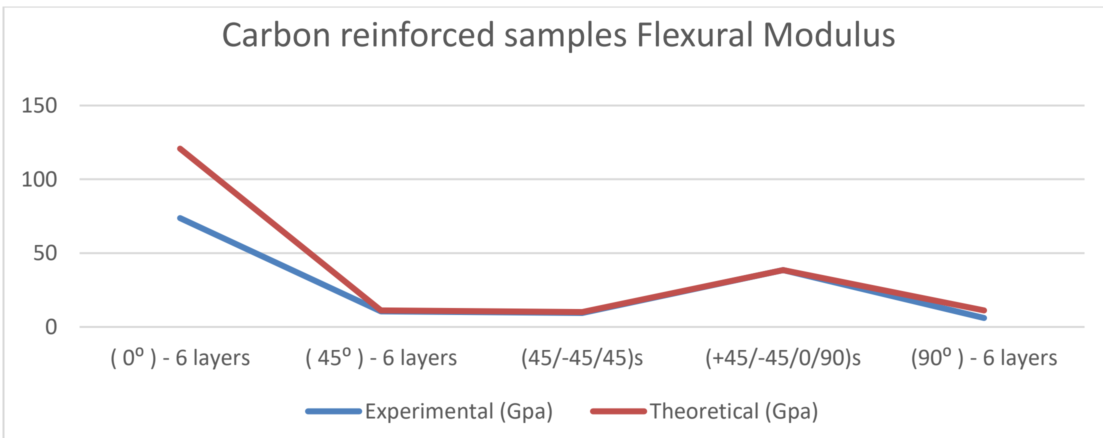


Figure 4.4: Codes validation accuracy for tensile modulus from literature

4.3.2 Codes Validation for flexural modulus

Table 4.8: Codes validation for flexural modulus from literature [34]

	Flexural Modulus			
Fiber	**Samples**	**Experimental (GPa)**	**Theoretical (GPa)**	**% error**
Carbon	(0^o) - 6 layers	73.75	120.78	-64%
Carbon	(45^o) - 6 layers	10.5	11.2	-7%
Carbon	(45/-45/45)s	9.5	10.11	-6%
Carbon	(+45/-45/0/90)s	38.53	38.55	0%
Carbon	(90^o) - 6 layers	6.07	11.29	-86%
Glass	(0^o) - 6 layers	26.25	40.36	-54%
Glass	(45^o) - 6 layers	8.11	8.55	-5%
Glass	(45/-45/45)s	7.67	9.22	-20%
Glass	(+45/-45/0/90)s	14.31	14.98	-5%
Glass	(90^o) - 6 layers	4.45	8.6	-93%



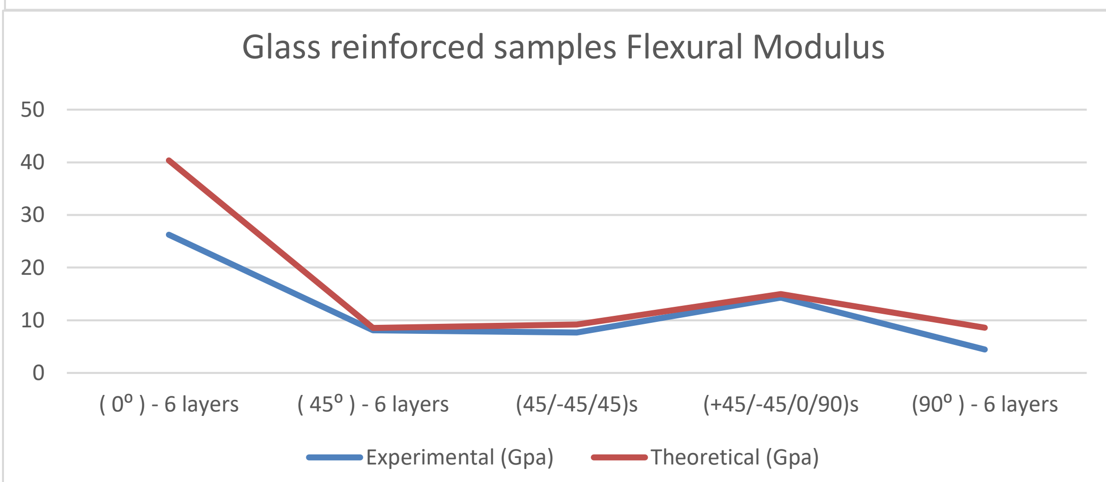


Figure 4.5: Codes validation accuracy for flexural modulus from literature

4.4. Codes Validation for tensile modulus from Experimental results

Tensile modulus values of the carbon-epoxy composites with 1:1 weight ratio fabricated using vacuum assisted microwave curing are compared with the codes results. To confirm the experimental results, we done the experiment 5 times for each sample.

Table 4.9: Properties of the used materials

Properties of Materials		
Properties	**Carbon fiber**	**Epoxy Matrix**
Tensile Modulus (GPa)	240	3
Shear Modulus (GPa)	15	1.1
Poisson's ratio	0.3	0.28

Longitudinal Modulus (GPa)	121.5
Transverse Modulus (GPa)	11.37
Shear Modulus (GPa)	2.77
Major Poisson Ratio	0.29
Minor Poisson Ratio	0.00716

4.4.1 Sample of $(0^o)_6$ orientation

Table 4.10: Codes validation for tensile modulus for (0^o) orientation

Tensile Modulus			
Samples	**Experimental (GPa)**	**Theoretical (GPa)**	**% error**
(0^o) - 6 layers	112.35	120.5	7%
(0^o) - 6 layers	105.67	120.5	12%
(0^o) - 6 layers	114.76	120.5	5%
(0^o) - 6 layers	103.58	120.5	14%
(0^o) - 6 layers	108.06	120.5	10%

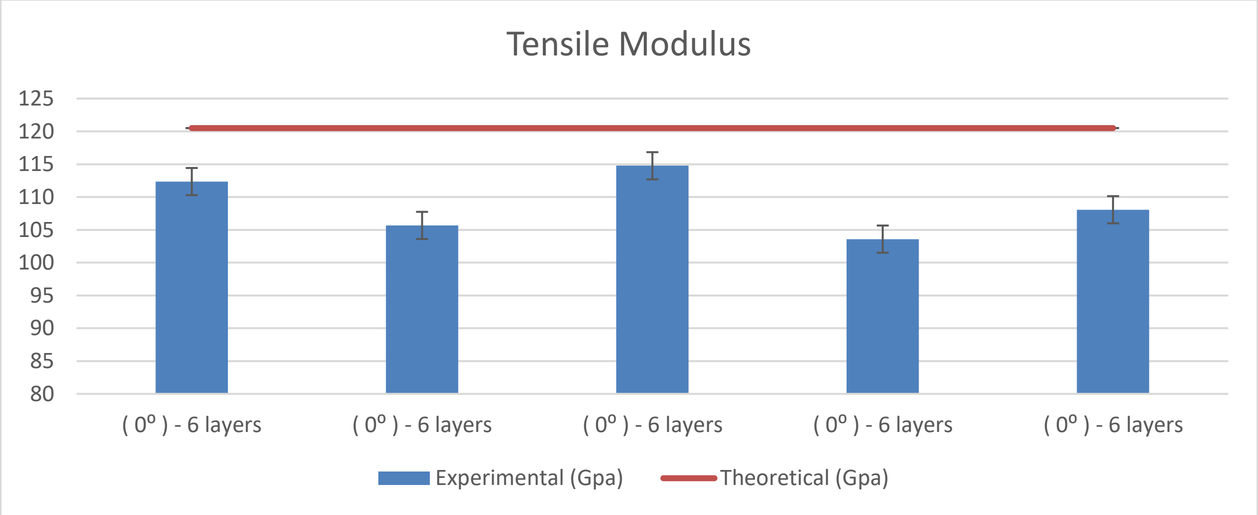


Figure 4.6: Codes validation accuracy for tensile modulus for (0^o) orientation

4.4.2 Sample of $(0/90)_3$ orientation

Table 4.11: Codes validation for tensile modulus for $(0/90)_3$ orientation

Tensile Modulus			
Samples	Experimental (GPa)	Theoretical (GPa)	% error
(0 / 90) 3	63.2	66.4	5%
(0 / 90) 3	61.7	66.4	7%
(0 / 90) 3	58.5	66.4	12%
(0 / 90) 3	56.8	66.4	14%
(0 / 90) 3	59.4	66.4	11%

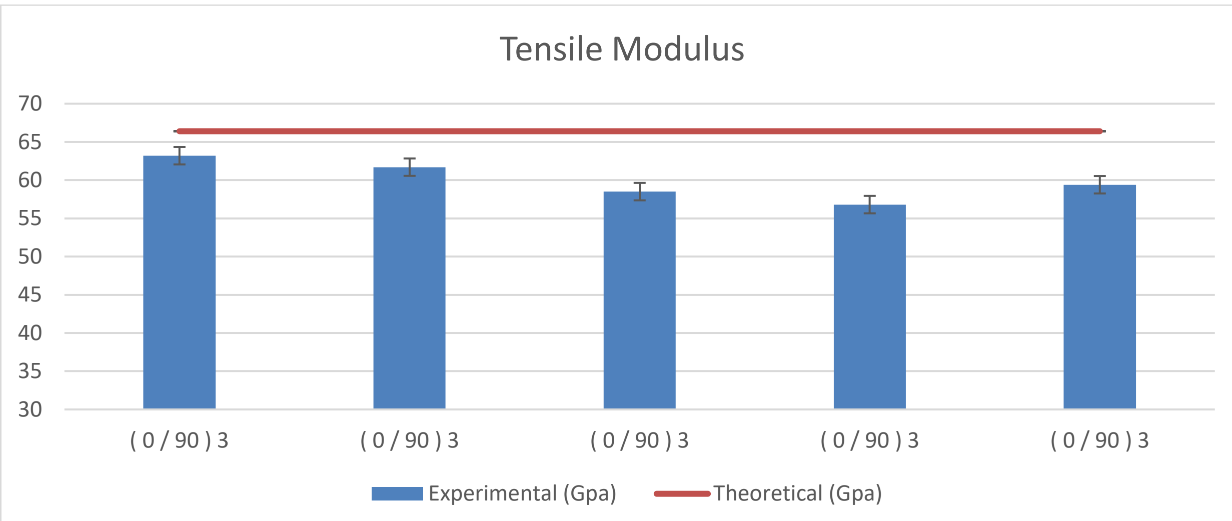


Figure 4.7: Codes validation accuracy for tensile modulus for $(0/90)_3$ orientation

4.4.3 Sample of $(45/-45)_3$ orientation

Table 4.12: Codes validation for tensile modulus for $(45/-45)_3$ orientation

Tensile Modulus			
Samples	Experimental (GPa)	Theoretical (GPa)	% error
(+45 / -45)3	7.6	10.26	26%
(+45 / -45)3	6.8	10.26	34%
(+45 / -45)3	8.3	10.26	19%
(+45 / -45)3	8.1	10.26	21%
(+45 / -45)3	8.4	10.26	18%

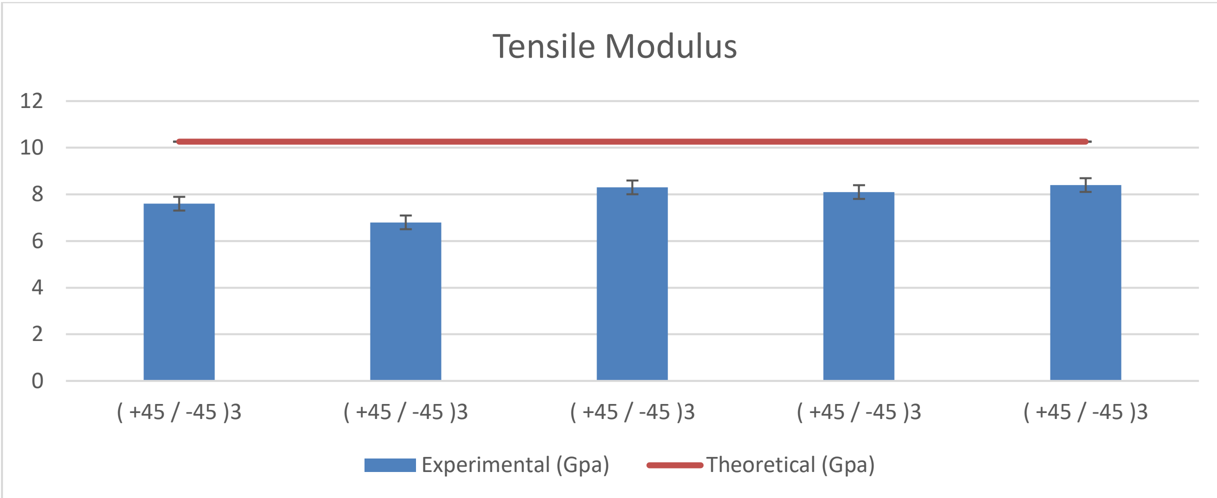


Figure 4.8: Codes validation accuracy for tensile modulus for $(0/90)_3$ orientation

4.5 Summary

Results for various samples are analysed and compared with the python codes. For computational results, we get a very good accuracy. To improve the mechanical properties, we use vacuum assisted microwave curing and results shows a significant increase in the tensile modulus values. The values that we get for the fabricated samples are very close to the predicted values. We found that the tensile modulus values are in $(0)_6 > (0/90)_3 > (45/-45)_3$ this order. The flexural values from the literature also shows a good resemblance with the predicted values except for the pure longitudinal (0^0) and transverse direction (90^0) samples.

CHAPTER 5
CONCLUSION

5.1 Conclusions

This study on development of open-source python codes for the prediction of the mechanical properties of laminates leads to the following conclusions:

- Fabrication of the unidirectional carbon epoxy samples using vacuum assisted microwave curing has been done successfully.
- The development of python codes to predict the stress distributions, tensile modulus, shear modulus and flexural modulus has also been done successfully.
- Codes shows the least deviation or error (less than 15%) for the samples that are fabricated through vacuum assisted microwave curing.
- The highest tensile modulus of value 114 GPa has been seen in the $(0^o)_6$ orientation sample and the predicted value for this sample is 120 GPa.
- Codes works well for the computational results; less than 10% error is seen in general for the stress distributions inside each layer of laminate.
- Vacuum assisted microwave curing can helps in fast and defect free fabrication of samples. The samples are cured in approximately 10 minutes with a 540 W microwave.

5.2 Scope for Future Research

The present study on codes development leaves a wide scope for upcoming researchers to continue this work. Few recommendations can be:

- In the present study, we only compare the tensile modulus values through experiments, this work can be extended further to study the effect of orientation angles on the shear and flexural modulus and the results can be validated through the codes.
- In the present study, we only consider the carbon epoxy laminates but the codes can be applied to other polymer composites also.
- The codes are based on the classical laminated theory, researchers can build machine learning models and can create a open source application for the prediction of various mechanical properties in the laminates.

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GitHub Link for Python Codes…….

Link: https://github.com/Mr-Lokesh/MTechReportCode

Python Code

```
import math
import numpy as np
import pandas as pd
# -----------------------------------Input Parameters -----------------------
---------------------
vol_frac_fiber = float(input("Enter volume fraction of fiber:  "))
young_mod_fiber = float(input("Enter Young's Modulus (in Mpa) of fiber:  "))
young_mod_matrix = float(input("Enter Young's Modulus (in Mpa) of Matrix:
"))
shear_mod_fiber = float(input("Enter Shear Modulus (in Mpa) of fiber:  "))
shear_mod_matrix = float(input("Enter Shear Modulus (in Mpa) of Matrix:  "))
poisson_ratio_fiber = float(input("Enter poisson's ratio of fiber:  "))
poisson_ratio_matrix = float(input("Enter poisson's ratio of matrix:  "))
# -----------------------------------------------------------------------------
-------------------



#  Longitudinal Modulus
uni_longi_mod = young_mod_matrix *
(vol_frac_fiber*((young_mod_fiber/young_mod_matrix)-1)+1)
print("\nLongitudinal modulus of composite: ",uni_longi_mod)

# Transverse Modulus
ratio = (young_mod_fiber / young_mod_matrix)
eta = (ratio - 1) / (ratio + 2)
trans_mod = young_mod_matrix * (1 + (2*eta*vol_frac_fiber)) / (1 -
(eta*vol_frac_fiber))
print("Transverse Modulus value is: ",trans_mod)

# Shear Modulus
shear_mod_ratio = (shear_mod_fiber / shear_mod_matrix)
eta = (shear_mod_ratio - 1) / (shear_mod_ratio + 1)
shear_mod = shear_mod_matrix * (1 + (1 * eta * vol_frac_fiber)) / (1 - (eta *
vol_frac_fiber))
print("Shear Modulus value (in Mpa) is: ", shear_mod)

# Poisson's Ratio
poisson_LT = (poisson_ratio_fiber * vol_frac_fiber)+(poisson_ratio_matrix*(1-
vol_frac_fiber))
print("Major Poisson's Ratio is:   ", poisson_LT)

uni_longi_mod = young_mod_matrix * (vol_frac_fiber * ((young_mod_fiber /
young_mod_matrix) - 1) + 1)
poisson_LT = (poisson_ratio_fiber * vol_frac_fiber) + (poisson_ratio_matrix *
(1 - vol_frac_fiber))
poisson_TL = (young_mod_matrix / uni_longi_mod) * poisson_LT
print("Minor Poisson's Ratio is:   ",poisson_TL)
```

Calculation of Mechanical Properties

```
A11,A12,A22,A16,A26,A66,B11,B12,B16,B22,B26,B66,D11,D12,D16,D22,D26,D66 =
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
sum = 0
var = 0

orientation = []
thickness = []
Z_elements_from_top = []
list_stress_values_X = []
list_stress_values_Y = []
list_stress_values_XY = []
list_stress_values_L = []
list_stress_values_T = []
list_stress_values_LT = []
list_location = []

list_stress_values_top = []
list_stress_values_bottom = []

#-----------------------------------------------------Input Layers ----------
------------------------------
print("\n")
layers = int(input("Enter number of layers in laminate:   "))
n = layers

for i in range(layers):
    height = float(input("Enter thickness of layer"+str([i+1])+" from top:
"))
    thickness.append(height)
    angle = float(input("Enter orientation angle of layer"+str([i+1])+" in
degrees:   "))
    orientation.append(angle)
# ----------------------------------------------------------------------------
-------------------------------
# Calculation of Z values for each layer according to thickness
for j in range(0, len(thickness)):
    sum = sum + thickness[j]
median = sum / 2

for j in range(0, len(thickness)):
    if j == 0:
        Z_elements_from_top.append(-median)

    var = var + thickness[j]
    z_value = var - median
    Z_elements_from_top.append(z_value)

print("\nOrientation angle from top to bottom: ",orientation)
print("Thickness of each layer from top to bottom: ",thickness)
```

```python
for i in range(layers):
    # uni_longi_mod = float(input("\nEnter longitudinal elastic modulus of
layer"+str([i+1])+":  "))
    # trans_mod = float(input("Enter transverse elastic modulus of
layer"+str([i+1])+":  "))
    # shear_mod = float(input("Enter shear modulus of layer"+str([i+1])+":
"))
    # poisson_LT = float(input("Enter major poisson ratio of
layer"+str([i+1])+":  "))
    # poisson_TL = float(input("Enter minor poisson ratio of
layer"+str([i+1])+":  "))

    theta = orientation[i]
    sine = (math.sin(math.radians(theta)))
    cosine = (math.cos(math.radians(theta)))

    Q11 = uni_longi_mod / (1 - (poisson_LT * poisson_TL))
    Q22 = trans_mod / (1 - (poisson_LT * poisson_TL))
    Q12 = (poisson_LT * trans_mod) / (1 - (poisson_LT * poisson_TL))
    Q66 = shear_mod

    Q11_bar = Q11 * (cosine ** 4) + Q22 * (sine ** 4) + 2 * (Q12 + (2 * Q66))
* (sine ** 2) * (cosine ** 2)
    Q22_bar = Q11 * (sine ** 4) + Q22 * (cosine ** 4) + 2 * (Q12 + (2 * Q66))
* (sine ** 2) * (cosine ** 2)
    Q12_bar = (Q11 + Q22 - (4 * Q66)) * (sine ** 2) * (cosine ** 2) + Q12 *
((cosine ** 4) + (sine ** 4))
    Q66_bar = (Q11 + Q22 - (2 * Q12) - (2 * Q66)) * (sine ** 2) * (cosine **
2) + Q66 * ((cosine ** 4) + (sine ** 4))
    Q16_bar = (Q11 + Q12 - (2 * Q66)) * (cosine ** 3) * (sine) - (Q22 - Q12 -
(2 * Q66)) * (sine ** 3) * (cosine)
    Q26_bar = (Q11 + Q12 - (2 * Q66)) * (cosine) * (sine ** 3) - (Q22 - Q12 -
(2 * Q66)) * (sine) * (cosine ** 3)

    A11 = A11 + thickness[i] * float(Q11_bar)
    A22 = A22 + thickness[i] * float(Q22_bar)
    A12 = A12 + thickness[i] * float(Q12_bar)
    A66 = A66 + thickness[i] * float(Q66_bar)
    A16 = A16 + thickness[i] * float(Q16_bar)
    A26 = A26 + thickness[i] * float(Q26_bar)

    B11 = B11 + (((Z_elements_from_top[i + 1] ** 2) - (Z_elements_from_top[i]
** 2)) / 2) * float(Q11_bar)
    B22 = B22 + (((Z_elements_from_top[i + 1] ** 2) - (Z_elements_from_top[i]
** 2)) / 2) * float(Q22_bar)
    B12 = B12 + (((Z_elements_from_top[i + 1] ** 2) - (Z_elements_from_top[i]
** 2)) / 2) * float(Q12_bar)
    B66 = B66 + (((Z_elements_from_top[i + 1] ** 2) - (Z_elements_from_top[i]
** 2)) / 2) * float(Q66_bar)
    B16 = B16 + (((Z_elements_from_top[i + 1] ** 2) - (Z_elements_from_top[i]
** 2)) / 2) * float(Q16_bar)
    B26 = B26 + (((Z_elements_from_top[i + 1] ** 2) - (Z_elements_from_top[i]
** 2)) / 2) * float(Q26_bar)
```

```
    D11 = D11 + (((Z_elements_from_top[i + 1] ** 3) - (Z_elements_from_top[i]
** 3)) / 3) * float(Q11_bar)
    D22 = D22 + (((Z_elements_from_top[i + 1] ** 3) - (Z_elements_from_top[i]
** 3)) / 3) * float(Q22_bar)
    D12 = D12 + (((Z_elements_from_top[i + 1] ** 3) - (Z_elements_from_top[i]
** 3)) / 3) * float(Q12_bar)
    D66 = D66 + (((Z_elements_from_top[i + 1] ** 3) - (Z_elements_from_top[i]
** 3)) / 3) * float(Q66_bar)
    D16 = D16 + (((Z_elements_from_top[i + 1] ** 3) - (Z_elements_from_top[i]
** 3)) / 3) * float(Q16_bar)
    D26 = D26 + (((Z_elements_from_top[i + 1] ** 3) - (Z_elements_from_top[i]
** 3)) / 3) * float(Q26_bar)
A_matrix = np.matrix([
    [A11, A12, A16],
    [A12, A22, A26],
    [A16, A26, A66]])

B_matrix = np.matrix([
    [B11, B12, B16],
    [B12, B22, B26],
    [B16, B26, B66]])

D_matrix = np.matrix([
    [D11, D12, D16],
    [D12, D22, D26],
    [D16, D26, D66]])

print("\n [A]  Matrix:")
print("-------------------------------------------------------------------")
print(A_matrix)
print("-----------------------------------------------------------------\n")

print("\n [B]  Matrix:")
print("-------------------------------------------------------------------")
print(B_matrix)
print("-----------------------------------------------------------------\n")

print("\n [D]  Matrix:")
print("-------------------------------------------------------------------")
print(D_matrix)
print("-----------------------------------------------------------------\n")

Stiffness_matrix = np.matrix([
        [A11 , A12 , A16 , B11 , B12 , B16],
        [A12 , A22 , A26 , B12 , B22 , B26],
        [A16 , A26 , A66 , B16 , B26 , B66],
        [B11 , B12 , B16 , D11 , D12 , D16],
        [B12 , B22 , B26 , D12 , D22 , D26],
        [B16 , B26 , B66 , D16 , D26 , D66]
    ])
Inverse_stiffness_matrix = Stiffness_matrix.getI()
Inverse_D_matrix = D_matrix.getI()
Inverse_A_matrix = A_matrix.getI()
#print(Stiffness_matrix)
tensile_modulus_E11 = 1/ (sum * Inverse_A_matrix[0,0])
shear_modulus_G12 = 1/ (sum * Inverse_stiffness_matrix[2,2])
flexural_modulus = 12 / ((sum**3) * Inverse_D_matrix[0,0])
```

```
print("Tensile Modulus (E11):  ", tensile_modulus_E11)
print("Shear Modulus (G12):  ", shear_modulus_G12)
print("Flexural Modulus:  ", flexural_modulus)
```

Calculation of stress distribution inside the layers

```
N_x = float(input("\nEnter stress in 'X' direction:   "))
N_y = float(input("Enter stress in 'Y' direction:   "))
N_xy = float(input("Enter shear stress in 'XY' direction:   "))
M_x = float(input("Enter moment in 'X' direction:   "))
M_y = float(input("Enter moment in 'Y' direction:   "))
M_xy = float(input("Enter moment in 'XY' direction:   "))

NM_matrix = np.matrix([
        [N_x],[N_y],[N_xy],[M_x],[M_y],[M_xy]
    ])

Strain_curvature_matrix = Inverse_stiffness_matrix * NM_matrix

laminate_strains = Strain_curvature_matrix[0:3,0:]
laminate_curvature = Strain_curvature_matrix[3:,0:]

for i in range(0, len(Z_elements_from_top)):
    #print("\nStrains in " + str([i + 1]) + " layer from top:")
    lamina_strain = laminate_strains + Z_elements_from_top[i] *
laminate_curvature



for i in range(layers):
    # long_elastic_mod = float(input("\nEnter longitudinal elastic modulus of
layer"+str([i+1])+":  "))
    # trans_elastic_mod = float(input("Enter transverse elastic modulus of
layer"+str([i+1])+":  "))
    # shear_mod = float(input("Enter shear modulus of layer"+str([i+1])+":
"))
    # poisson_LT = float(input("Enter major poisson ratio of
layer"+str([i+1])+":  "))
    # poisson_TL = float(input("Enter minor poisson ratio of
layer"+str([i+1])+":  "))
    theta = orientation[i]
    sine = (math.sin(math.radians(theta)))
    cosine = (math.cos(math.radians(theta)))

    Q11 = uni_longi_mod / (1 - (poisson_LT * poisson_TL))
    Q22 = trans_mod / (1 - (poisson_LT * poisson_TL))
    Q12 = (poisson_LT * trans_mod) / (1 - (poisson_LT * poisson_TL))
    Q66 = shear_mod

    Q11_bar = Q11 * (cosine ** 4) + Q22 * (sine ** 4) + 2 * (Q12 + (2 * Q66))
* (sine ** 2) * (cosine ** 2)
    Q22_bar = Q11 * (sine ** 4) + Q22 * (cosine ** 4) + 2 * (Q12 + (2 * Q66))
* (sine ** 2) * (cosine ** 2)
```

```
    Q12_bar = (Q11 + Q22 - (4 * Q66)) * (sine ** 2) * (cosine ** 2) + Q12 *
((cosine ** 4) + (sine ** 4))
    Q66_bar = (Q11 + Q22 - (2 * Q12) - (2 * Q66)) * (sine ** 2) * (cosine **
2) + Q66 * ((cosine ** 4) + (sine ** 4))
    Q16_bar = (Q11 + Q12 - (2 * Q66)) * (cosine ** 3) * (sine) - (Q22 - Q12 -
(2 * Q66)) * (sine ** 3) * (cosine)
    Q26_bar = (Q11 + Q12 - (2 * Q66)) * (cosine) * (sine ** 3) - (Q22 - Q12 -
(2 * Q66)) * (sine) * (cosine ** 3)

    deformation_xy_top = laminate_strains + (Z_elements_from_top[i] *
laminate_curvature)
    deformation_xy_bottom = laminate_strains + (Z_elements_from_top[i + 1] *
laminate_curvature)
    # print("\n For z =  " + str([i]) + "deformations are: ", deformation)

    # Conversion of deformation matrix from x-y to L_T plane.
    transformation_matrix = np.matrix([
        [(cosine ** 2), (sine ** 2), (sine * cosine)],
        [(sine ** 2), (cosine ** 2), ((-1) * sine * cosine)],
        [((-2) * sine * cosine), (2 * sine * cosine), ((cosine ** 2) - (sine
** 2))]
    ])
    deformation_LT_top = transformation_matrix * deformation_xy_top
    deformation_LT_bottom = transformation_matrix * deformation_xy_bottom
    Q_bar_matrix = np.matrix([
        [Q11_bar, Q12_bar, Q16_bar],
        [Q12_bar, Q22_bar, Q26_bar],
        [Q16_bar, Q26_bar, Q66_bar]])

    stress_values_top_XY_cor = Q_bar_matrix * deformation_xy_top
    stress_values_bottom_XY_cor = Q_bar_matrix * deformation_xy_bottom

    stress_values_top_LT_cor = Q_bar_matrix * deformation_LT_top
    stress_values_bottom_LT_cor = Q_bar_matrix * deformation_LT_bottom
    # print("\n For layer " + str([i+1]) + " stress values on top side are:
\n", stress_values_top)
    # print("\n For layer " + str([i+1]) + " stress values on bottom side
are: \n", stress_values_bottom)

    location_top = "layer" + str([i + 1]) + " top:  "
    location_bottom = "layer" + str([i + 1]) + " bottom:  "

    list_location.append(location_top)
    list_location.append(location_bottom)

    # Converting stress
    # _values matrix elements into list.

    list_stress_values_X.append(stress_values_top_XY_cor.item(0, 0))
    list_stress_values_X.append(stress_values_bottom_XY_cor.item(0, 0))
    list_stress_values_Y.append(stress_values_top_XY_cor.item(1, 0))
    list_stress_values_Y.append(stress_values_bottom_XY_cor.item(1, 0))
    list_stress_values_XY.append(stress_values_top_XY_cor.item(2, 0))
    list_stress_values_XY.append(stress_values_bottom_XY_cor.item(2, 0))

    list_stress_values_L.append(stress_values_top_LT_cor.item(0, 0))
    list_stress_values_L.append(stress_values_bottom_LT_cor.item(0, 0))
```

```
    list_stress_values_T.append(stress_values_top_LT_cor.item(1, 0))
    list_stress_values_T.append(stress_values_bottom_LT_cor.item(1, 0))
    list_stress_values_LT.append(stress_values_top_LT_cor.item(2, 0))
    list_stress_values_LT.append(stress_values_bottom_LT_cor.item(2, 0))

    list_stress_values_top.append(stress_values_top_LT_cor.item(0, 0))
    list_stress_values_top.append(stress_values_top_LT_cor.item(1, 0))
    list_stress_values_top.append(stress_values_top_LT_cor.item(2, 0))

    list_stress_values_bottom.append(stress_values_bottom_LT_cor.item(0, 0))
    list_stress_values_bottom.append(stress_values_bottom_LT_cor.item(1, 0))
    list_stress_values_bottom.append(stress_values_bottom_LT_cor.item(2, 0))

stress_state_in_XY_plane = pd.DataFrame({
    'Location': list_location,
    'Sigma_X': list_stress_values_X,
    'Sigma_Y': list_stress_values_Y,
    'Tau_XY': list_stress_values_XY
})
stress_state_in_XY_plane.set_index('Location', inplace=True)
print("\n------------------------------ Stress State in XY plane -------------
--------------------\n")
print(stress_state_in_XY_plane)
print("----------------------------------------------------------------------
----------------------")

stress_state_in_LT_plane = pd.DataFrame({
    'Location': list_location,
    'Sigma_L': list_stress_values_L,
    'Sigma_T': list_stress_values_T,
    'Tau_LT': list_stress_values_LT
})
stress_state_in_LT_plane.set_index('Location', inplace=True)
print("\n------------------------------- Stress State in LT plane-------------
--------------------\n")
print(stress_state_in_LT_plane)
print("----------------------------------------------------------------------
--------------------")
```