CHAPTER.1 INTRODUCTION

1.1 Composites:

Composites are structural materials which are made up of two or more ingredients at macroscopic level and both phases are not soluble in each other. The properties of obtained material are different from individual constituents. This is done to gain benefit from both material properties. There are generally two phases in composites. One is reinforcing phase which is discontinuous and provides strength to structure while other on is continuous phase which protects reinforcing phase from environmental damage and transfers load to reinforcing phase. Reinforcement phase can be particles, fiber or flakes while matrix may be polymeric, ceramic or metallic. Sometimes due to processing and chemical reaction an interphase exists between reinforcing phase and matrix phase. The difference between composite and alloys is that in alloys we mixed at microscopic level while in composite in macroscopic level. And the properties of alloys material is different from basic mixing element while in composites retain their individual properties. The properties of composite depend on properties of fiber and matrix, and geometry and distribution of phases. One of the important parameter is volume fraction of reinforcement phase. Distribution of reinforcement phase determines homogeneity of system. The more non uniform distribution of reinforcement phase less homogenous will be system. The geometry and distribution of reinforcement phase determines anisotropy of material.

The phases in composite materials play different role according to applications. In the case of low to medium applications short fiber or particles are used as reinforcement phase. In this case matrix is mainly load bearing phase and reinforcing phase is only limited to provide strength. In the case of high strength composite structures long fibers are used to provide directional stiffness and strength. Due to rapid advancement in almost every industry, composite materials are emerging chiefly in response to unprecedented demands from technology. Our intensive studies about fundamental nature of materials and better understanding of their structure is allowing us to develop new composite materials with improved and enhanced physical, mechanical properties. Also composites has high strength to weight ratio,that is why about 15% of the available engineering materials in market are composite that makes composite a more important material in today’s world.

1.2 Advantages of composite materials:

Composites are widely used in engineering structure because high strength to weight ratio and now it is a challenge for us to make them cost effective. In an effort to produce economical composite components, several manufacturing techniques are being employed in the composite industry. Monolithic metals and their alloys are far behind than composites, in meeting the demands of advanced technologies that are being used in recent time. Composite materials offer unique mechanical properties that include improved strength, high stiffness, long fatigue life, low density, than other available materials. In addition to these properties composites have good flexibility to perform the indented function of the structure. Few desirable properties like appearance, thermal insulation and conductivity, corrosion resistance, wear resistance, environmental stability, and acoustic insulation, can be realised for additional improvements. In the anisotropic and heterogeneous character of the material, high specific strength and high specific stiffness are two main properties that are the basis of the super structural performance of composite materials.

But the fact is that, the improvement in manufacturing technology is not satisfactorily sufficient to overcome the economic hurdle. So it is quiet essential that that should be a combined effort in various prospects like material, designing, processing, tooling, manufacturing, and quality assurance. The commercial applications of composites offer much larger business opportunities than the aerospace sector due to the unmitigated size of transportation industry. The entrance of these advanced materials has witnessed a steady expansion in its uses and applications. High performance fibre reinforced polymer (FRP) can now be seen in such diverse applications as fuel cylinders of gas vehicles, windmill blades, drive shafts in industries, rollers for paper making and even support beams of highway bridges. The need of composite for lighter construction materials has emphasised the use of new and advanced materials that not only reduces dead weight but also works as shock absorber.

1.3 Classification of Composites:

Classification of composites is done on the basis of the geometry of the reinforcement and type of matrix. Geometry of reinforcement includes particulate, flake, and fibers. Whereas the composites classified according to type of matrix include polymer, metal, ceramic, and carbon. Composites are briefly classified as illustrated in the table below.

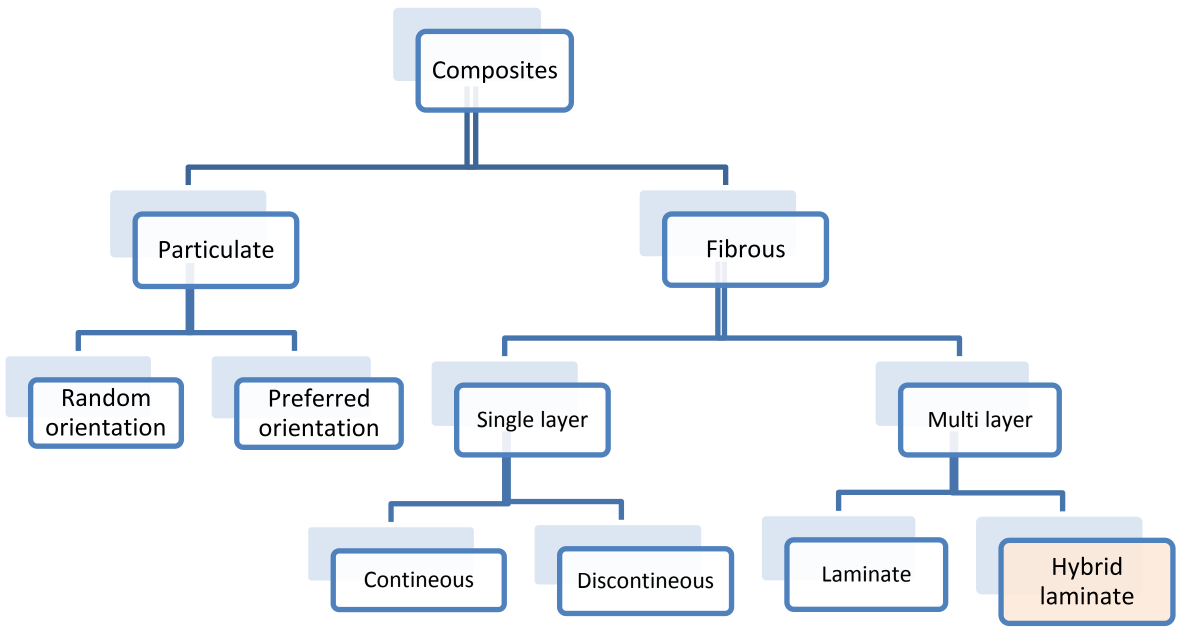

Fig. 1.1 Classification of composites

Particulate composites contain large amounts of comparatively coarse particles and these particles of different sizes, shapes are randomly dispersed within the matrix. Particulate composites are widely used class of composites due to their wider availability and cost effectiveness. The usual random particle distribution makes the composite as quasi-homogeneous and quasi-isotropic on a macro scale. At macro scale the particle size and spacing is much larger than the existing one. Particulate composites may be tailored in a number of combinations like non-metallic particles in a non-metallic matrix, metallic particles in non-metallic matrices, metallic particles in metallic matrices and many more.

Fibrous reinforced composite hold improved strength-to-weight ratio and other mechanical properties. The high strength-to-weight ratio is achieved by incorporating stiff, strong but brittle fibers into a more ductile and soft matrix. Most off the applied load is transferred to the fibers through matrix medium. The matrix also helps to protect the fibers from external loads and atmosphere. Further, fibrous composites are classified into two categories namely single layered and multi layered composites**.**

Single layered composite is sub divide into continuous and discontinuous composites. Continuous reinforcement possesses the highest strength and stiffness. Discontinuous fibers are used only when manufacturing economics impose the use of a process where the fibers must be in desired discontinuous form. Fiber-reinforced composites accomplish mechanical properties because of fiber properties and also the degree by which external load is transferred to fibers by matrix phase.

The **multi layered** composites are sub divided into laminate and hybrid laminate. Laminated composites are tailored using one fiber and one matrix system in a laminate. The laminas can be oriented at different angles with different stacking sequence. The orientation of lamina denotes the angle at which fibers are oriented in a lamina. Hybrid composites may contain more than one type of fiber and matrix system in a laminate. The development of multi-layered fibre reinforced laminated composite is going with a rapid pace over the last few decades and has opened a doorway for usage of composites in a number of applications such as aerospace, automotive parts, and many other areas. Laminates of composites are characterised by their anisotropic nature. In-plane alignment of reinforced fibers makes the composites robust, in-plane mechanical properties. Out of the plane properties, in-plane properties have been outlined to be superior in laminated composites. The laminated composites suffer from cracking and delamination under axial compression, bending and impact loading, which limits the applications of these composite materials in engineering.

Further, Hybrid composite is explained in detail below.

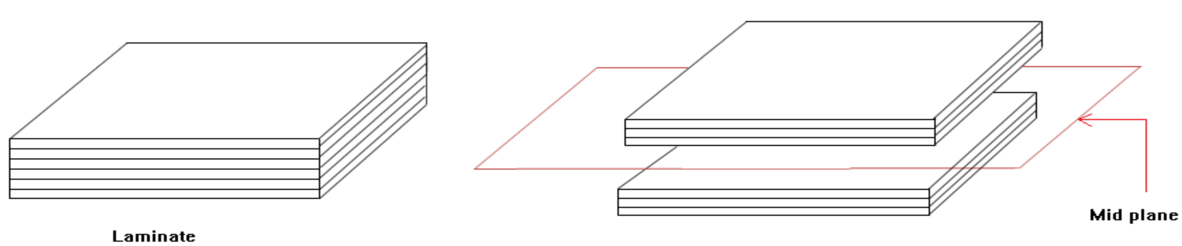

Fig. 1.2 Mid plane of a laminate

1.3.1 Hybrid Laminated Composite:

Presently, hybrid composites are established with high efficiency and high performance structural materials. A rapid increase in use of hybrid composites for different applications, has led the researchers to show a deep interest in investigation of such materials with enhanced properties. These composites have applications when a combination of properties is desired at the same time, or when longitudinal performance along with lateral mechanical performance is required. Several different laminas may be incorporated into a hybrid laminate, but it is more likely that a combination of only two types of laminas is used It has been already explained that hybrid composites consist of two or more fibres and matrix system. Particularly, combination of glass fiber with stiffer carbon fibers has been a lively interest in recent years. Though carbon fibers are more expansive but are being widely used in a number of applications. Many evidences prove that hybrid composites offer a more attractive combination of properties i.e. toughness and stiffness, than those composites which are based on a single fiber type. Because of high strength-to-weight ratio, low cost, ease of fabrication and unique mechanical properties hybrid composite materials have been used in extensive engineering applications. Hybrid composites hold combination of properties such as tensile modulus, compressive strength, and impact strength which cannot be realised in composite materials.

For example:

A combination of Graphite-Epoxy (ID1) with Glass-Epoxy lamina (ID2) may be used to fabricate a hybrid laminate. Here lamina of two different fiber and matrix system are stacked together where each layer can be laid at various orientations. Suppose the laminate consist of 4 layers and is fabricated using two kinds of materials. So the stacking sequence for this hybrid laminate may be of different orders i.e.1st layer with material ID1, 2nd layer with material ID2, 3rd layer with material ID1, 4th layer with material ID2, and many more depending upon the requirement.

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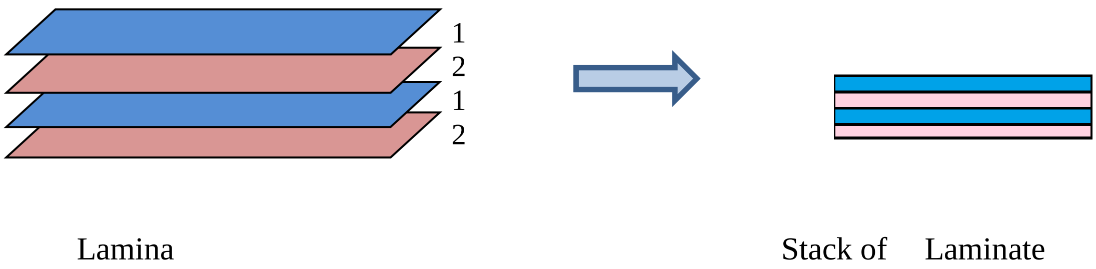


Fig. 1.3 Hybrid laminated composite

1.4 Classification of Hybrid Laminates

Hybrid laminates can be classified as follows-

1.41 Interply hybrid laminate

In this type plies are made of two or more material system. For e.g. car bumpers are made of two types of material, glass/epoxy and graphite/epoxy.

1.4.2 Intraply hybrid laminate

Two or more different fibers are used in the same ply in intralply hybrid laminate system. Golf clubs made up of Graphite and Aramid fibers.

1.4.3 Interply-Intraply laminate

This type of laminate system contains different fibers in same ply and also distinct composite system in more than one ply

1.4.4 Resin hybrid laminate

When two or more resin is used instead of combining two or more fiber in laminate, resin hybrid laminates are formed. In this type one resin is flexible and the other one is rigid.

1.5 Mechanics of laminated composites:

The mechanics of laminated composite materials is generally studied at two distinct levels commonly called micromechanics and macromechnics.

1.5.1 Micromechanics This level is used to study the interaction between fibres and matrix in a lamina such that the mechanical behaviour of lamina could be predicted from the known behaviour of its constituents. At this study level, the behaviour of composite material is assumed homogeneous and the effects of the constituent material are detected only as averaged apparent properties of the composite material.

1.5.2 Macromechanics

A laminate is made of two or more lamina glued together to act as an integral structural element. The various laminas are oriented with (local) principal material directions at different angles to the global laminate axes to produce a structural element capable of resisting load in several directions. The stiffness and strength of such a composite material structures configuration are obtained from the properties of constituent lamina. At macro mechanical level, stress-strain behaviour of composites using effective properties of an equivalent homogenous material is studied. Only the globally averaged stresses and strains are considered. Or we can say that the interaction of the constituent material is examined in detail as part of the definition of the heterogeneous composite material.

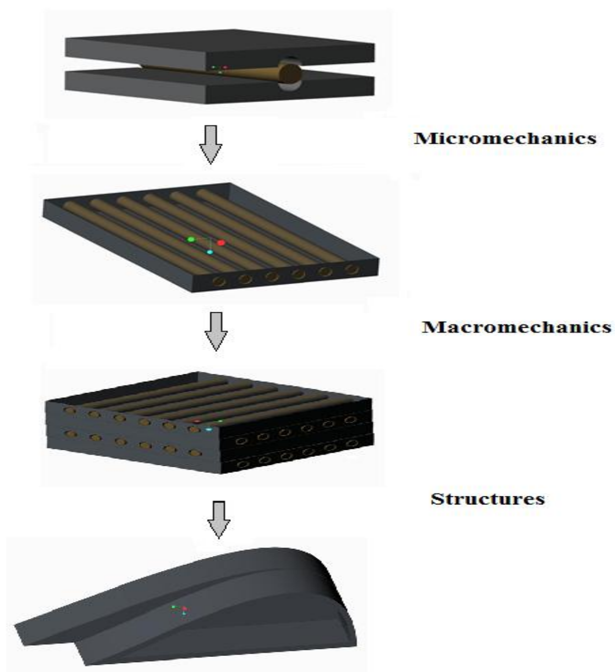


Fig. 1.4 Mechanics of laminated composites

1.6 Applications of hybrid laminated composite:

Golf clubs use both aramid and graphite fibers. Here the strength and toughness is achieved by aramid fibers whereas torsional rigidity is achieved by graphite fibers.

Car bumpers are fabricated using glass/epoxy and graphite/epoxy layers, where glass/epoxy layers offer torsional rigidity, whereas graphite/epoxy layers offer stiffness. And the combinations of these two material systems lower the cost of bumper.

Beam structures made up of composites are being widely used for commercial and aerospace applications like aeroplane wing rotor blade etc. The use of composite materials for making composite beam is due to -

- Improved performance of beam
- Saving of material to a significant amount
- Minimum mass under strength constraints
- High strength/stiffness-to-weight ratio
- Excellent fatigue and corrosion resistance properties

So in view to all above advantages of hybrid laminated composite are being designed using hybrid laminated composite materials. The physical and mechanical properties of materials are related to the geometry shapes of structures while designing the lightweight high stiffness composite beam. For the safety and reliability performance of composite beam to large extent failure pressure is most important factor among a variety of design parameters. The accurate prediction of failure pressure and damage evolution properties of composite beam, serves as a safe and economic design of composite beam.

1.7 Aim of Thesis

This thesis is based on parametric study of hybrid lamina. There have been taken two types of lamina one is graphite-epoxy and other is glass-epxoy lamina. Both the laminas are laminated to find the best stacking sequence of lamina and ply orientation. Ansys software is used to analyse the hybrid laminated structure.

Following cases are investigated in the present work:

- Validation of semi-clamped graphite-epoxy laminated plate
- Modeling of graphite-epoxy and glass-epoxy hybrid laminated composite in ANSYS
- Study the behavior of stacking sequence, ply orientation and number of lamina

- Determination of failure index of hybrid laminated composite for different stacking sequences using ANSYS
- Modeling of laminated hybrid clamped-clamped and clamp-free rectangular plate in ANSYS
- Determination of deflection of clamped-clamped and clamped-free rectangular plate using ANSYS

1.8 Thesis Outline

For compressive view of the field of parametric study and optimization it is necessary to bring together science, failure theory, and classical laminated theory. This thesis begins by covering these areas before, moving on to showing the original new work in the subsequent chapters. Hence the thesis is organised as follows.

Chapter 1: Contains introduction of composite, in this part detail explained about composites and types of composite. Also explained why composite is widely used in the recent time. The application composite are mentioned in the introductory part.

Chapter 2: Contains comprehensive literature review of the field of the field laminated structures which demonstrate detailed literature review of the most commonly used in laminated composite structure. Different types of failure criteria, classical lamination theory etc. application are studied in this section.

Chapter 3: This chapter contains material and method which is used in laminated structure. This discussion includes some laws which deals laminated structure and assumption which is made in theoretical formula. This section also contains procedure of modelling of hybrid laminated model in Ansys.

Chapter 4: Represents the results obtained after parametric study of laminated plate in different parametric condition. This chapter also contains validation of kam et al 1996 paper which was based on laminated plate of different boundary condition and ply orientation.

Chapter 5: Summarizes the work carried out for this thesis.

CHAPTER.2 REVIEW OF LITERATURE

Manders *et al* (1981) evaluated the tensile properties of hybrid composites fabricated using glass/carbon fiber in epoxy matrix, over a range of glass and carbon ratio and also over the states of dispersion of two phases. It was also observed that, relative decrease in the proportion of carbon fibers and fine dispersion of carbon fibers resulted in an increased the failure strain of carbon phase. And this behavior of composite is termed as the hybrid effect. A total of 50% enhancement was observed in the failure strain. In the carbon phase, a small effect is assigned to internal compression strains induced due to differential thermal shrinkage on cooling the composite to its cure temperature. The failure mode is of multiple failure type where the laminae made up of the carbon fibers are dispersed in the matrix of glass or glass fiber phase. He also proposed that when a considerable number of laminae fracture accumulates the catastrophic failure occurs. Progressive failure occurred and material shows good toughness than other equivalent carbon fiber composites. The existence of hybrid effect is totally dependent on the ratio of two fiber types and on the dispersion of these two fiber types. Less extensible and stiffer shows a higher failure strain when fibers are more finely dispersed and occupy a low volume proportion. He also observed that carbon fiber reinforced polymer show a progressive failure mode. The stiffness in such hybrid composites is enhanced initially but brittle and catastrophic failure mode of all fibers is avoided.

Kretsis *et al* (1987) presented a review on tensile, compressive, shear and flexural properties of hybrid laminated composites. In this study author concluded that the tensile modulus of hybrid composite can be obtained from the rule of mixture, while classical laminate theory can be used to determine the flexural stress. Author worked with different models of continuous – fiber reinforced hybrids to predict the mechanical properties with some special emphasis. Hybrids used in his work are mostly of unidirectional materials, as multidirectional materials require some additional variables for investigation. In literature concerns most of the data available is for carbon and glass hybrid reinforced epoxy composites, as these composites have wider range of properties under varying external circumstances. Regrettably, the main concern in this review is with the controversial hybrid effect. Author has reviewed that most of the investigators used a commodious variety of carbon fiber, glass fiber and epoxy resin type that has made direct comparison a cumbersome. Correct comparison parameters estimate the elastic properties using rule of mixture. Author defined the controversial term hybrid effect on the basis of tensile tests of hybrids and proposed that the failure stress of low elongation material is increased. The mechanical properties like tensile , compression and flexural strength of hybrids are not up to the predictions made by rule of mixture, whereas the shear strength nearly follows a linear trend. Author also concluded that hybrid composites cannot be superior to single fiber composites until and unless all other aspects of structural designs are considered.

Reddy et al.(1992) studied on linear and nonlinear failure analysis on graphite epoxy composite laminates using FEM. First ply lamination schemes and loading condition. They implemented Maximum stress, Maximum Strain, Tsai-Hill, Hoffman criteria to predict the failure load.

They found that linear first ply failure load and nonlinear first ply failure load is maximum in case of transverse loading whereas minimum in in case of in in-plane tensile loading with clamped edge boundary conditions. They also concluded that the difference between linear and nonlinear failure load is large for thin laminates with simply supported boundary condition and much small for thick laminates for clamped edge boundary conditions

Kam *et al.* (1996) developed a new finite element method for predicting the nonlinear behaviour of thin laminated composite plates. His method was based on the principle of minimum potential energy and von Karman-Mindlin plate theory. In this work load-displacement curve for Graphite-Epoxy laminate with various lamination schemes are examined and then plotted. The obtained curves were compared with the curves that were determined experimentally in literature. To predict the first ply failure load, various failure theories were implemented for laminates. No stiffness reduction criteria were applied to calculate the failure load of laminates. Some of the important remarks of his studied are briefly explained below-

- Finite element method predicts best load-displacement curve and ultimate strength when nine node Lagrangian elements are used.
- For first ply failure load of plates Maximum stress, Hoffman and Tsai-Hill failure criteria provide good results.

- The developed method was unable to predict actual failure mechanism hence modification in stiffness reduction method is suggested.

T.Y. Kam *et al* (1997) studied strength of laminated composite pressure vessels by analytical and experimental methods for various laminae stacking sequences. First ply failure strength of pressure vessel made up of graphite/epoxy laminates, is calculated using both analytical and experimental methods. Author used the experimental approach to determine the first-ply failure and burst strength of pressure vessel, with different stacking sequence of laminae. In analytical approach various theories are used for predicting the first-ply failure strengths, on the basis of various failure criterions. For reliability as well as economical vessels, the accurate predictions of first-ply failure strength is necessary, therefore a meaningful reliability assessment is performed by author. It is concluded that the analytical methods together with Hoffman failure criteria or maximum stress criteria, predict the accurate failure pressure for laminated composite vessels. Also a comparison is done using results of ultimate burst pressure for the laminated composite pressure vessels. Generally, for laminated composite pressure vessel the ultimate burst pressure has much higher value than first-ply failure pressure. At last it is concluded that laminated composite pressure vessels can be appropriately designed using first ply failure criteria.

Joo *et al.* (2000) performed progressive failure analysis on cross-ply and quasi-isotropic laminates subjected to in plane tensile loads. A 3-D finite element analysis was developed based on generalized layer wise plate theory. To perform failure analysis various failure criteria and property degradation methods are used. A rectangular plate made up of HFG-CU125NS graphite- epoxy laminate with four different laminate sequences are used for analysis. Mesh refinement is performed at free edges of laminates. Hashin failure criteria is used for failure analysis of laminates. The stiffness reduction method is also implemented for maintaining accuracy of failure analysis. Fiber bundle theory for fiber failure and matrix-lag method is used for matrix cracking. The conclusions of present investigation can be summarized as-

- The value of transverse tensile stress at free edges is higher for those quasi-isotropic laminates in which 90° layers are used in midplane rather than 45° layers.

- Failure load in the case of cross plies is almost same for $[0_5/90]_s$ and $[0/90_5]_s$ laminates at 90̊ layer due to negligible interlaminar shear stresses.
- Matrix failure load for quasi-isotropic laminates having 90̊ layers in midplane is 89% less than laminates having 45̊ layers in midplane.

Kumar *et al.* (2003) introduced a new stiffened plate element for finite element analysis of laminated composite plate with stiffeners. First ply failure load of cross ply laminated stiffened plates is predicted by performing finite element analysis. First ply failure load is calculated for uniformly distributed and sinusoidal loading conditions. The new introduced element is made by combining Allman's plane stress triangular element and Kirchhoff-Mindlin triangular plate bending element. The element is capable to accommodate number of arbitrary oriented stiffeners.

The rectangular symmetric cross ply laminate with rectangular stiffener is analysed. Due to symmetric boundary conditions quarter plate is modelled and plate is discretized into 4x4 and 8x8 mesh sizes. Simply support boundary conditions and uniformly distributed loads are applied on plate. Various failure theories such as Tsai-Wu, maximum stress, Hoffman and Yeh-Stratton are applied to determine first ply failure load. A parametric study is performed on various stiffeners sections i.e. blade, I-section and hat stiffener. The stiffeners and plate is made up of 10 layers of [ϴ/-ϴ/ ϴ/-ϴ/ ϴ/-ϴ/ ϴ/-ϴ/-ϴ/ ϴ] angle plies and ϴ is varied from 15̊ to 75̊. Parametric study revealed that first ply failure load for blade stiffened panels is higher than I- section when fiber orientation angle is less than 45̊ but for angles greater than 45̊ I- sections shows higher failure loads.

Pal *et al.* (2007) performed progressive failure analysis of laminated composite plates under transverse and static loading conditions. Eight-noded isoparametric bending element is used to model laminated plate. Shear deformation theory is used for analysis. Mid surface of plate is considered as the reference surface. Stiffness degradation model is used for progressive failure analysis. Whenever a lamina fails its stiffness is reduced from rigidity matrix and new rigidity matrix of laminate is calculated for remaining laminae. Elastic constants for failed lamina are taken as zero and new values of elements of rigidity matrix are calculated as a function of material properties, geometry and stacking sequence of lamina. This procedure is continued until no lamina remains for failure. Following investigations are made in present study-

- A rectangular plate of size 228.6mmX 127mm with varying number of layers is studied. Plate is made up of T300/5208 graphite-epoxy composite material and subjected to uniformly distributed transverse load.
- Rectangular plate with asymmetric and symmetric laminated configuration is considered for analysis. Quarter of plate is modeled due to symmetry.

The outcome of present investigation can be concluded as-

- For the symmetric and asymmetric laminates ultimate failure load increases with increase in angle of fiber orientation.
- Failure load varies exponentially with fiber angles when numbers of layers are four or six.
- The variation of failure load with number of layers is hyperbolic.
- For symmetric cross ply laminates failure load decreases with increase in aspect ratio and increases with increase in thickness of lamina.

Banerjee *et al* (2013) performed a micromechanical analysis of carbon and glass fibers of a unidirectional composite using finite element method. Author assumed the hybrid composites with circular fibers packed in hexagonal array. He studied the relative locations of two different fibers within the unit cell and the effect of two different fiber volume fractions. Shear modulus and transverse modulus of hybrid composites are predicted using modified Tsai equations. A study is also made for two fibers having same volume fraction are placed at different locations to determine the variability in mechanical properties of two fibers. Transverse strength properties showed a significant variation. He also made a comparison between the single fiber composites and hybrid composites. Carbon and glass fibers have a random location within a volume element at given volume fraction of fibers in his computational model. As the fiber locations are varied a considerable effect on transverse strength is noticed in hybrid composites but has no effect on stiffness properties. Since stiffness is a volume averaged quantity therefore the fiber position does not show any effect. An empirical relation is derived for predicting the shear modulus, longitudinal Poisson’s ratio and transverse stiffness that is similar to Halpin-Tsai equations. And these properties are predicted to a good level of accuracy using Tsai equations. To predict the strength direct micromechanics is used, that is based on first element failure method. A considerable estimate for failure initiation is provided.

Overall, this work aimed at developing a compatible computational model so that the hybrid composites cab be tested at different volume fraction of reinforcements. A study was also made to examine the effect of hybridization on various mechanical properties of composites. For future reference, the same model can be used for analysing the progressive damage in hybrid composites.

Rahimi *et al.* (2012) failure behavior of laminated composite plate is predicted using commercially available finite element software ANSYS and FORTRAN. A simply supported rectangular plate is subjected to uniaxial load. A finite element program is developed in FORTRAN-90 using higher shear deformation theory to calculate stresses in lamina. Finite element model is validated by comparing central deflection of plate with published literature. Maximum stress and Tsai-Wu failure criteria are implemented to predict failure load. The average error between finite element software and finite element program is found below 16%.

Uniyal, et al. (2016) studied laminated composite they analysed unidirectional and angle ply laminates of different fibre orientation angles and concluded that cantilever beam with fibre orientation along the direction of loading shows maximum failure strength whereas unidirectional and angle ply laminates with 45 degree fibre orientation shows minimum strength.

Zhang *et al* (2016) presented a review paper on the latest development of complex laminated composite structures which were totally based on finite element analysis since 1990. The review comprised of various theories of composite structures but it mainly emphasized on first ply failure, damage and failure analysis of composite plates. Reddy and Robbins analyzed the single and multi-layered composite structures using various theories. Liu and Li also analyzed laminated plates and made overall comparison of results obtained using displacement hypothesis. Altebach worked on laminated composite plates and sandwich plates. Ghugal and

Shimpi reviewed the displacement and shear deformation theory of laminated composite structures having isotropic and anisotropic behavior. Carrera presented review of work done till 2003, on zigzag theories of multi-layered laminated plates and shells. Paper presented an overall review on the recent advances, based on finite element analysis of laminated composite plates using various theories of lamination. Author investigated the damage and failure analysis of composite structures and proposed some aspects for future research. Some of these are listed below-

- Effects of materials non-linearity on the behaviour of composite laminates
- Under repeated loading, failure analysis and damage can be performed
- Damage analysis at micromechanical level
- Damage evolution analysis in composite structures
- Crack generation, its propagation and finally the failure of structure in multi-scale modeling.

Karamanlı, A., 2018. They applied the Ritz method with polynomial shape functions and found that auxiliary functions is simple to implement, efficient and provides quick convergence rates and expected results for the static analysis of laminated composite and sandwich beams.

3.1 Macromechanics of Lamina:

Composite materials are studied at various measurement scales. In macro mechanical scale, composites are analysed for a lamina where lamina is treated as homogeneous material. And the material properties are the averaged value of its constituent material properties.

Here unidirectional lamina is assumed to be orthotropic body, and the stress-strain relationship for 2D orthotropic material is expressed using equation (3.1), in matrix notation.

$$[\sigma] = [Q][\varepsilon] \tag{3.1}$$

Where,

$[\sigma]$ $is\ the\ stress\ matrix$

$[\varepsilon]$ $is\ the\ strain\ matrix$

$[Q]$ $is\ the\ stiffness\ matrix$

Further, strain-stress relation can be expressed using equation (3.2)

$$[\varepsilon] = [S][\sigma] \tag{3.2}$$

Where, $[S]$ $is\ the\ compliance\ matrix\ i.e. the\ inverse\ of\ the\ stiffness\ matrix$

On expanding the compliance matrix in equation (3.2) we have,

$$[\varepsilon] = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{21} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} [\sigma] \tag{3.3}$$

Where,

$S_{11} = \frac{1}{E_X}$, and E_X is Young's modulus in X direction

$S_{12} = \frac{-\nu_{XY}}{E_X}$, and ν_{XY}Poisson's ratio in XY plane

$S_{21} = \frac{-\nu_{YX}}{E_Y}$, and ν_{YX} is Poisson's ratio in YX plane

$S_{22} = \frac{1}{E_Y}$, and E_Y is Young's modulus in Y direction

$S_{66} = \frac{1}{G_{XY}}$, and Gxy is modulus of rigidity

3.1.1 Hook's law for 2-D Lamina:

Fiber-reinforced composites are considered as orthotropic therefore minimum two orthogonal symmetric planes are required. These material properties are direction independent within each plane and require nine material constants of constitutive matrices. In order to achieve higher strength and stiffness, laminas are stacked at different angles as lamina is weak in the direction perpendicular to fibers.

Therefore a stress-strain relationship for angle lamina is required. A local co-ordinate system is required to define each angle lamina. Fibers are defined along the longitudinal axis and have a transverse local axis perpendicular to fiber axis.

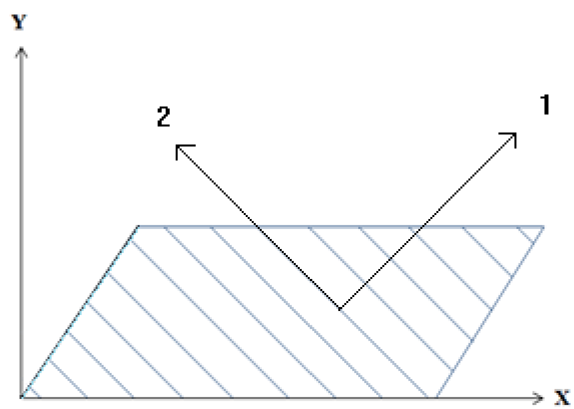


Fig. 3.1 Local and Global axis of a lamina

In above figure X-Y is the global axis whereas 1-2 is the material axis corresponding to fiber direction.

For a 2D angle lamina the Hook's law is given by equation (3.4)

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [T]^{-1}[Q][R][T][R]^{-1} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \tag{3.4}$$

Where,

$$[T] = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix},\ c = \cos(\theta)\ and\ s = \sin(\theta)$$

$$[Q] = Stiffness\ matrix$$

$$[R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix},\ Reuter's\ matrix$$

Equation (3.4) can be written as-

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11}^- & Q_{12}^- & Q_{16}^- \\ Q_{12}^- & Q_{22}^- & Q_{26}^- \\ Q_{16}^- & Q_{26}^- & Q_{66}^- \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \qquad \text{Or,} \tag{3.5}$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} S_{11}^- & S_{12}^- & S_{16}^- \\ S_{12}^- & S_{22}^- & S_{26}^- \\ S_{16}^- & S_{26}^- & S_{66}^- \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

Where,

$$[Q^-] = Reduced\ Stiffness\ matrix$$

$$[S^-] = Reduced\ Compliance\ matrix\ (inverse\ of\ reduced\ striffness\ matrix)$$

3.2 Macromechanical modeling of Laminates:

At micromechanical level where a laminate is modelled, the following assumptions are made according to the Classical Laminate Theory:

- Each lamina is considered as orthotropic.
- Each lamina is considered as homogenous.
- ε_{yz}, ε_{xz} shear strains are assumed to be zero.
- The laminate is assumed to be thin and laminate is subjected to in-plane loading($\sigma_z = \tau_{xz} = \tau_{yz} = 0$).
- Displacements are assumed to be continuous and small, throughout the laminate($|u|,\ |v|, |w| \ll |h|$).
- Each lamina is assumed to be elastic in nature.
- It is assumed that no slip occurs in between the adjacent layers.

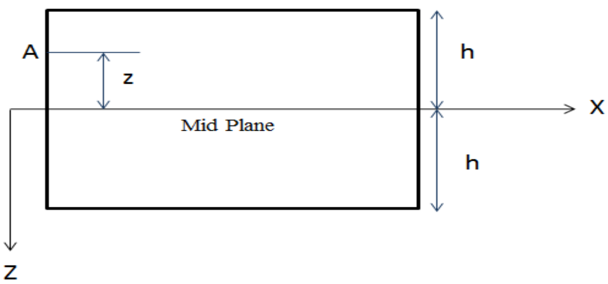


Fig. 3.2 Mid plane of a laminate

Strains in laminate can be written as

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} + z \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \quad (3.6)$$

Where,

$\varepsilon_x^0, \varepsilon_y^0, \varepsilon_{xy}^0$ are the mid-plane strains of the laminate and

K_x, K_y, K_{xy} are the curvatures,

'z' is the location of the point 'A' from the mid plane, where strain needs be determined.

We can calculate the global stresses, if strains are known along thickness of laminate. So from the stress-strain relationship for a lamina we have-

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11}^- & Q_{12}^- & Q_{16}^- \\ Q_{12}^- & Q_{22}^- & Q_{26}^- \\ Q_{16}^- & Q_{26}^- & Q_{66}^- \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \quad (3.7)$$

Where,

Q^- is the reduced stiffness matrix corresponding the point located in lamina, along the thickness of the laminate.

Using equation (3.6) and equation (3.7) for the laminate, we get

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11}^- & Q_{12}^- & Q_{16}^- \\ Q_{12}^- & Q_{22}^- & Q_{26}^- \\ Q_{16}^- & Q_{26}^- & Q_{66}^- \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} + z \begin{bmatrix} Q_{11}^- & Q_{12}^- & Q_{16}^- \\ Q_{12}^- & Q_{22}^- & Q_{26}^- \\ Q_{16}^- & Q_{26}^- & Q_{66}^- \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \quad (3.8)$$

Relation between Force and Moments in laminate are given by-

$$
\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \\ M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & B_{11} & B_{12} & B_{13} \\ A_{21} & A_{22} & A_{23} & B_{21} & B_{22} & B_{23} \\ A_{31} & A_{32} & A_{33} & B_{31} & B_{32} & B_{33} \\ B_{11} & B_{12} & B_{13} & D_{11} & D_{12} & D_{13} \\ B_{21} & B_{22} & B_{23} & D_{21} & D_{22} & D_{23} \\ B_{31} & B_{32} & B_{33} & D_{31} & D_{32} & D_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{bmatrix} \qquad (3.9)
$$

Where,

$[A]$ is extensional stiffness matrix, in which in-plane forces are related to in-plane strains.

$[D]$ is bending stiffness matrix, in which the resulting bending moments are related to the laminate curvatures.

$[B]$ is coupling matrix which couples the force and moment terms to the mid-plane strains and mid-plane curvatures.

And,

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

$$
\begin{bmatrix} M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} zdz
$$

Where,

$N_X,\ N_Y$ are the normal forces per unit laminate width.

N_{XY} is the shear force per unit laminate width.

$M_X,\ M_Y$ are the bending moment per unit laminate width.

M_{XY} is the twisting moment per unit laminate width.

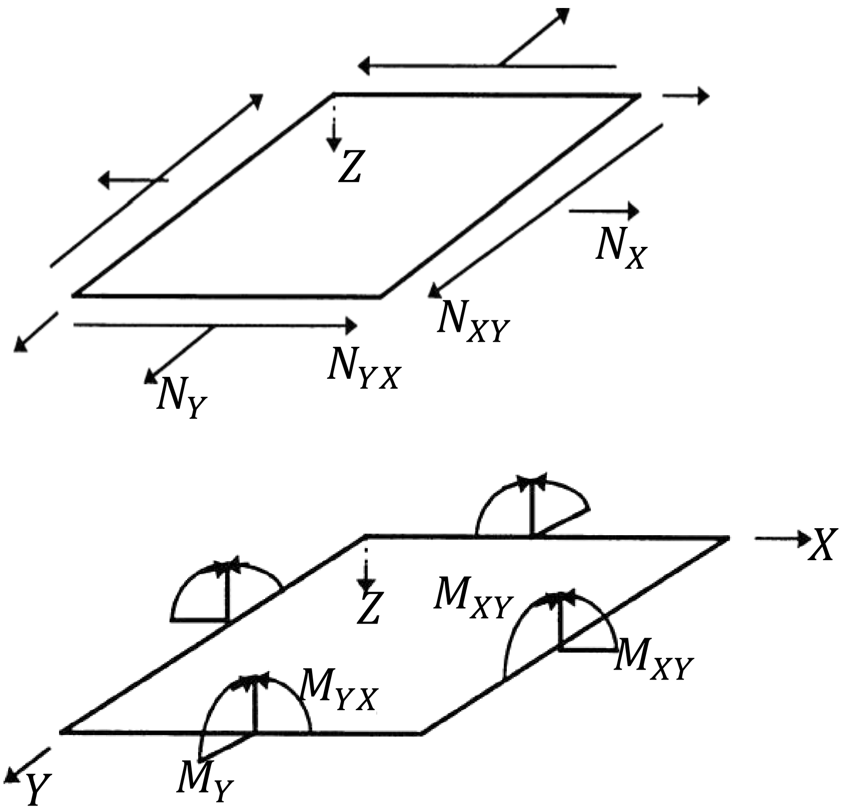


Fig. 3.3 Forces and moments acting on a laminate

3.3 Failure Theories for Lamina:

Failure of ductile material is predicted mainly using the yield criteria. Tresca and Rankine are commonly used failure theories to predict the failure of ductile materials.

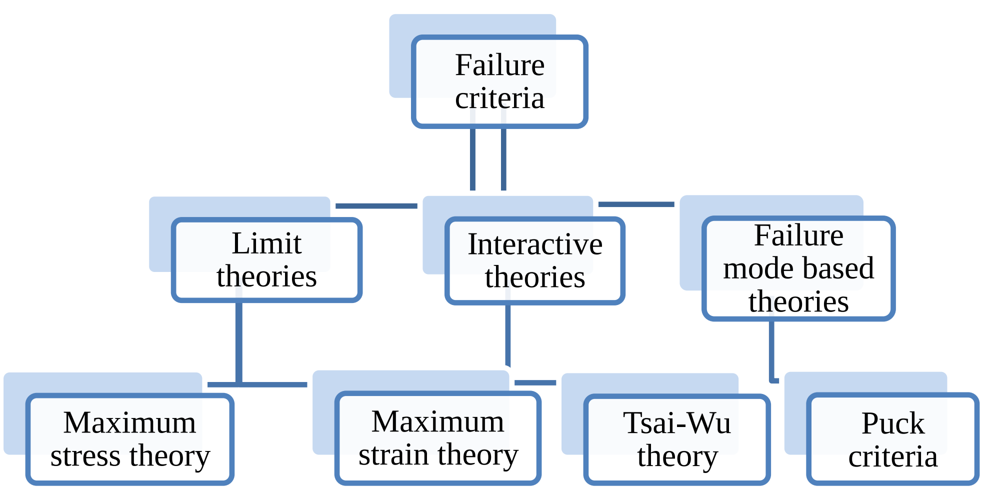
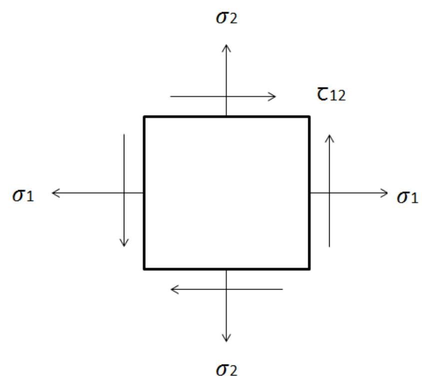


Fig. 3.4 Classification of failure criteria

3.3.1 Maximum stress failure theory: Tresca and Rankine are commonly used failure theories to predict the failure of ductile materials. According to these theories, failure will occur when the value of maximum stress exceeds the failure value of stress in uniaxial tensile test. If any one of the following conditions are violated the lamina is considered to be failed-



$-(\sigma_1^C)_{ult} < (\sigma_1) < (\sigma_1^T)_{ult}$

$-(\sigma_2^C)_{ult} < (\sigma_2) < (\sigma_2^T)_{ult}$

$-(\tau_{12})_{ult} < \tau_{12} < (\tau_{12})_{ult}$

Where,

$(\sigma_1^T)_{ult}$ is the ultimate tensile strength in longitudinal direction

$(\sigma_1^C)_{ult}$ is the ultimate compressive strength in longitudinal direction

$(\sigma_2^T)_{ult}$ is the ultimate tensile strength in transverse direction

$(\sigma_2^C)_{ult}$ is the ultimate compressive strength in transverse direction

$(\tau_{12})_{ult}$ is the ultimate in plane shear strength

3.3.2 Maximum strain failure theory: This theory is based on max. Strain theory of St. Venant. According to this theory lamina fails when values of strains in material axis exceed limiting values of strains.

Lamina is considered to be failed if any one of the following conditions violates-

$-(\varepsilon_1^C)_{ult} < (\varepsilon_1) < (\varepsilon_1^T)_{ult}$

$-(\varepsilon_2^C)_{ult} < (\varepsilon_2) < (\varepsilon_2^T)_{ult}$

$-(\gamma_{12})_{ult} < \gamma_{12} < (\gamma_{12})_{ult}$

Where,

$(\varepsilon_1^T)_{ult}$ is the ultimate tensile strain in longitudinal direction

$(\varepsilon_1^C)_{ult}$ is the ultimate compressive strain in longitudinal direction

$(\varepsilon_2^T)_{ult}$ is the ultimate tensile strain in transverse direction

$(\varepsilon_2^C)_{ult}$ is the ultimate compressive strain in transverse direction

$(\gamma_{12})_{ult}$ is the ultimate in plane shear strain

3.3.3 Tsai-Wu failure theory: This is interactive failure theory used for isotropic materials and is based on the strain energy. According to Tsai-Wu failure theory a lamina is considered to be safe, only when it satisfies the expression given by equation (A).

$$H_1\sigma_1 + H_2\sigma_2 + H_6\tau_{12} + H_{11}\sigma_2^2 + H_{66}\tau_{12}^2 + 2H_{12}\sigma_1\sigma_2 < 1 \qquad \textbf{(A)}$$

Where,

$$H_2 = \frac{1}{(\sigma_1^T)_{ult}} - \frac{1}{(\sigma_1^C)_{ult}}$$

$$H_{11} = \frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}}$$

$$H_2 = \frac{1}{(\sigma_2^T)_{ult}} - \frac{1}{(\sigma_2^C)_{ult}}$$

$$H_{22} = \frac{1}{(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}}$$

$$H_6 = 0,\ H_{66} = \frac{1}{(\tau_{12})_{ult}^2}\ H_{12} = -\frac{1}{2(\sigma_1^T)_{ult}^2},\ \text{as per Tsai} - \text{Hill failure theory}$$

$$H_{12} = -\frac{1}{2\sigma_1^T{}_{ult}\sigma_1^C{}_{ult}},\ \text{as per Hoffman criterion}$$

$$H_{12} = -\frac{1}{2}\sqrt{\frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}}}, \text{ as per Mises} - \text{Hencky criterion}$$

3.3.4 Tsai-Hill failure theory: Tsai-Hill failure theory is based on distortion energy theory for isotropic materials. According to this theory a lamina is considered fail when it does not satisfy the expression represented by equation (B).

$$(G_2 + G_3)\sigma_1^2 + (G_1 + G_3)\sigma_2^2 + (G_1 + G_2)\sigma_3^2 - 2G_3\sigma_1\sigma_2 - 2G_2\sigma_1\sigma_3 - 2G_1\sigma_3\sigma_2 + 2G_4\tau_{23}^2 + 2G_5\tau_{13}^2 + 2G_6\tau_{12}^2 < 1 \quad \textbf{(B)}$$

$$G_1 = \frac{1}{2}\left(\frac{2}{[(\sigma_2^T)_{ult}]^2} - \frac{1}{[(\sigma_1^T)_{ult}]^2}\right)$$

$$G_2 = G_3 = \frac{1}{2}\left(\frac{1}{[(\sigma_1^T)_{ult}]^2}\right)$$

$$G_6 = \frac{1}{2}\left(\frac{1}{[(\tau_{12})_{ult}]^2}\right)$$

As all above failure theories can be applied in order to determine the failure strength of a laminated composite but ANSYS is integrated with only two of these. The first one is Maximum Stress theory and the second one is Inverse Tsai-Wu theory. These two theories have been applied in order to determine the failure strength of the composite laminate.

3.4 Modeling and Finite Element Analysis of Laminates in ANSYS:

To model and solve complex real life systems finite element analysis has now integrated with Computer Aided Engineering (CAE). There are various finite element software packages are available in market such as ANSYS, ABAQUS, NASTRAN, FORTRAN etc. In present work ANSYS has been used as the tool for the modelling and analysis of laminated composite structures.

Structural analysis is used to predict the behaviour of engineering structures under the application of various loads. Structural analysis is generally conducted using analytical methods, experimental methods and numerical methods. Because of complexity of material properties, boundary conditions and structure itself analytical solutions are not suitable for many engineering problems. Therefore analytical methods are limited to a number of engineering applications. Numerical methods are widely used for engineering analysis which can analyse complex geometries also. ANSYS is based on Finite Element Method that is the most versatile numerical technique for solving engineering problems. In FEM, a body or structure is represented by a definite number of divisions called finite elements. Using FEM partial differential equation problems are translated to set of linear algebraic equations.

3.4.1 Steps involved in modeling of a composite laminate (ANSYS):

To start with the structural analysis in ANSYS, firstly we need to define the element type. It can be SHEEL or SOLID element type, depending upon the requirement. Once the element type has been defined we need to define the material properties, number of layers, and layer thickness and layer orientation within each element. To define the properties used in the model real constants (user defined characteristics) are used from the dialog window. In same dialog window the primarily option is to define the required number of layers in the model. After specifying the number of layers, composition of each layer is defined. Direction of the layer coordinate system relative to global coordinate system defines the layer orientation. Defining the layer thickness is the last step to model a laminated composite.

3.4.2 Modeling procedure with ANSYS

A complete analysis of a model in ANSYS is the logical interaction of three stages.

- PRE PROCESSING
- PROCESSING
- POST PROCESSING

And in a long winded manner we have to go through a number of sub stages within these 3 stages. The complete procedure is shown in diagram below.

Steps of finite element analysis in ANSYS-

3.4.2.1 Preprocessing

In preprocessing phase generally input parameters such as element type, material properties, layup and layer orientation, geometry, meshing, load and boundary conditions needs to be defined.

3.4.2.2 Geometry and Element type

In first step of performing the analysis, we need to define the geometry of model along with the element type. For modeling of the composite structures, layered SOLID and SHELL are element types among various available elements in ANSYS. If the thickness is negligible in comparison to its length and width, SHELL elements are used. We have large number of choices for selecting element type and selection is done accordingly. Selection of element type can either be made directly using command or by manually i.e. et.1, shell181 is command used to define the shell181 element. Some of common elements used in structural analysis with their characteristics are explained in table below.

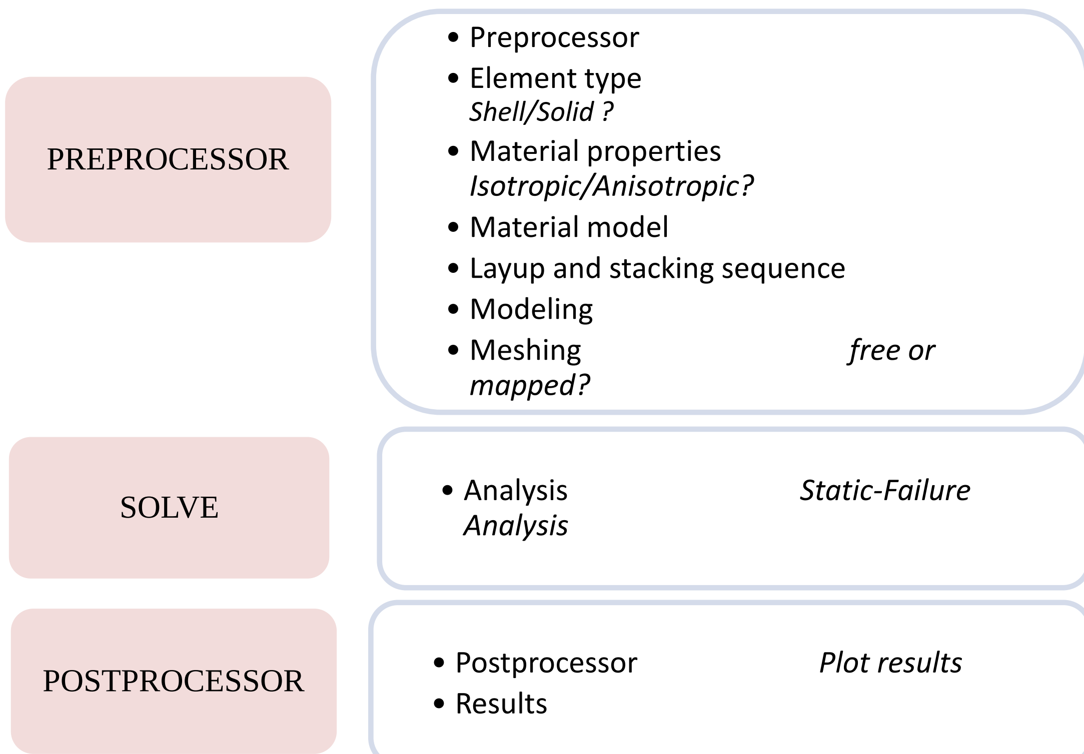


Fig. 3.6 Steps used in modeling with ANSYS

Common elements used for structural analysis:

Element name	**Description**
SHELL93	• Suitable for modeling curved shells • 8 node element with 6 DOFs at each node i.e. 3 translational and 3 rotational • Has quadratic deformation shapes both in-plane directions. • The element has plasticity, stress stiffening, large deflection, and large strain capabilities.
SHELL181	• Suitable for thin to moderately thick shell structures • Four node element with 6 DOFs at each node • Well suited for linear, large rotation, large strain in non-linear applications • May be used for layered composite shell structures.
SHELL281	• An 8-node element with 6 DOFs at each node • Suitable for analyzing thin to moderately-thick shell structures • Appropriate for linear, large rotation, and/or large strain nonlinear applications
SHELL99	• May be used for layered applications of a structural shell model • Allows up to 250 layers • Smaller element formulation time • Has 6 DOFs at each node • Uses less time for elements with 3 or more layers
PLANE82	• 8 node element with 2 DOFs i.e. translation in x and y direction • Suited to model curved boundaries • Provide more accurate results for mixed automatic meshes • Can tolerate irregular shape without much loss of accuracy • Common element for structural analysis

Some of these elements with their geometry are shown in figures below.

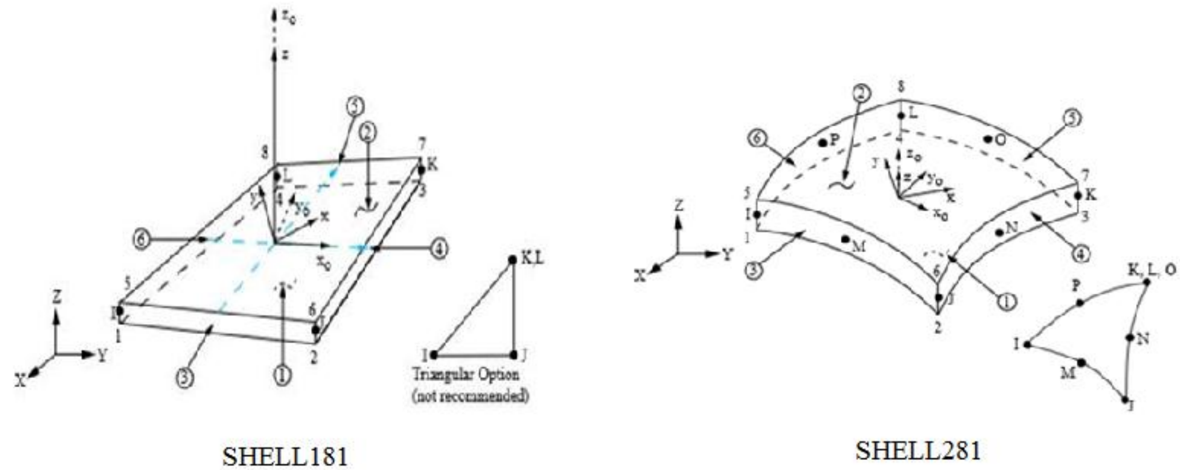


Fig. 3.7 Geometry of SHELL181 and SHELL281 element

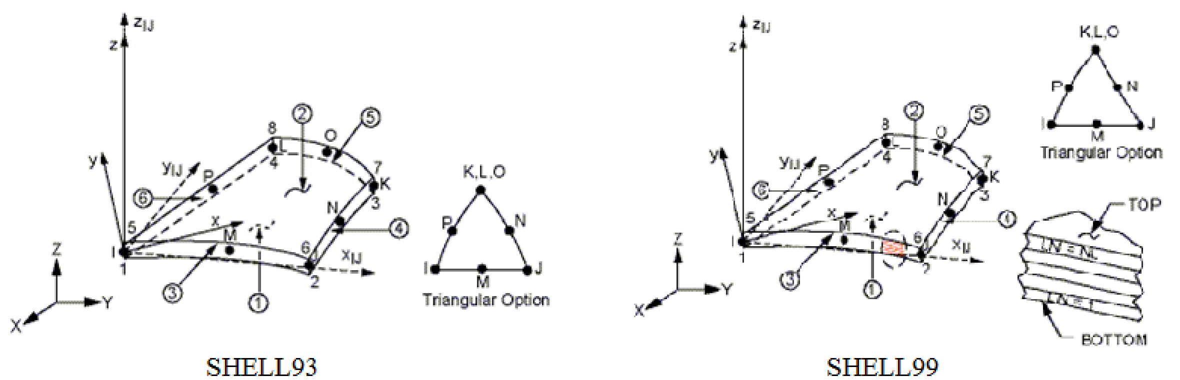


Fig. 3.8 Geometry of Shell93 and Shell99 element

3.4.2.3 Material Properties:

<u>Material Model-</u>

Material properties are used to define material behaviour like linear, nonlinear, isotropic, anisotropic or orthotropic, elastic or plastic etc. After defining material properties we need to define the elastic properties such as Young's modulus, Poisson's ratio and shear modulus.

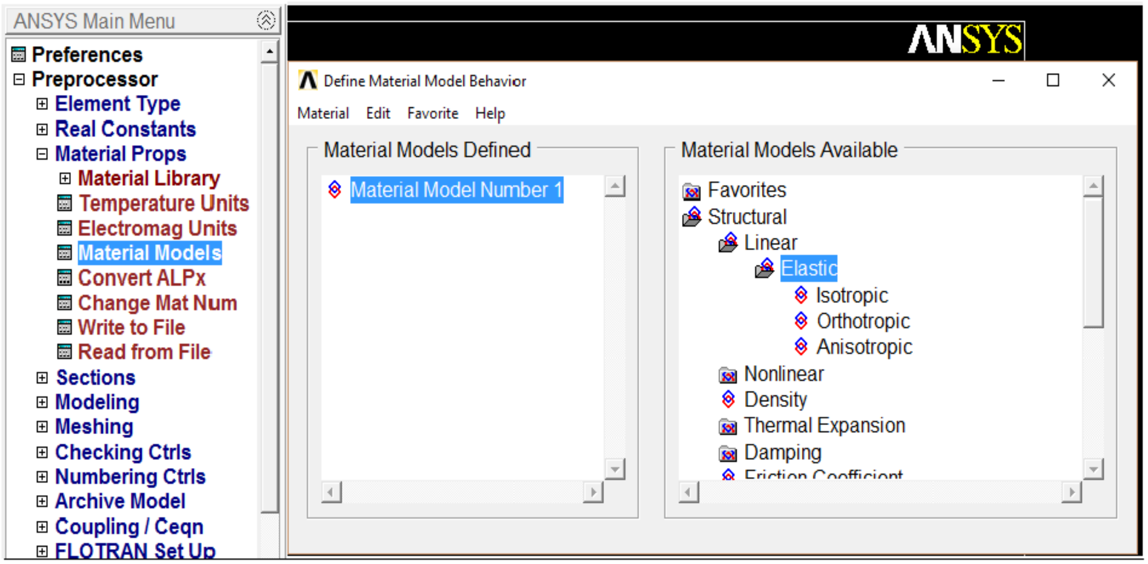


Fig. 3.9 Defining Material model in ANSYS

3.4.2.4 Defining Layup of Layers:

In create section, we can easily create and modify shell sections along with layup orientation. This section has flexibility of defining the layer thickness, material ID, orientation and pictorial visualization. Using plot section, arrangement of layers can be visualized as shown in figure below.

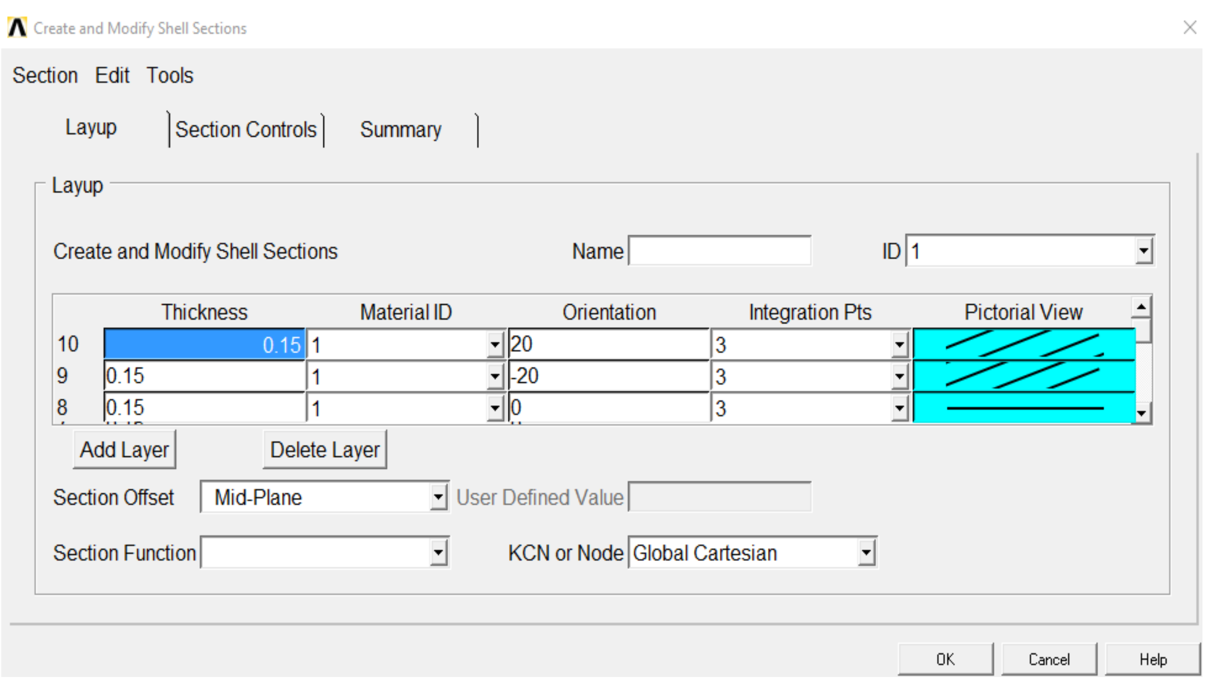


Fig. 3.10 Creating and modifying shell sections

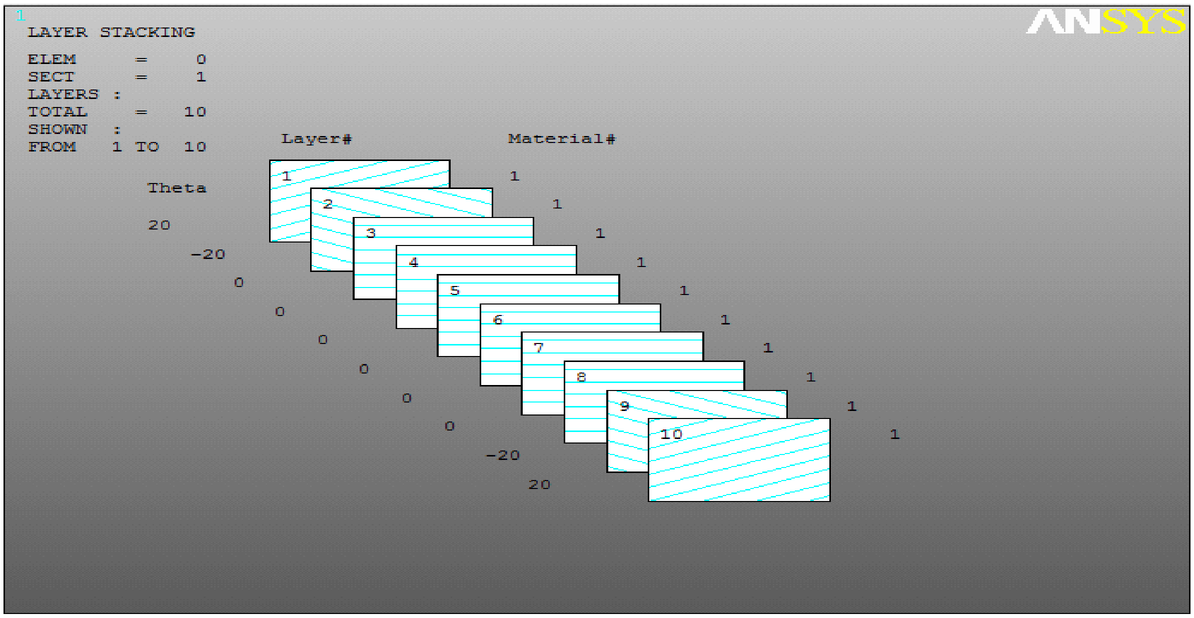


Fig. 3.11 Layer stacking at different orientation

3.4.2.5 Mesh Definition: Meshing of a solid model or geometry is done using mesh tool. Mesh Tool converts or divides the model into small finite elements. Certain steps are performed for meshing a solid model or geometry.

1. Select the geometry (or solid model) to be meshed
2. Define material and element type
3. Select type of meshing- free or mapped
4. Further, mesh can be refined again
5. Select the coordinate system to mesh different sections lying at different angles

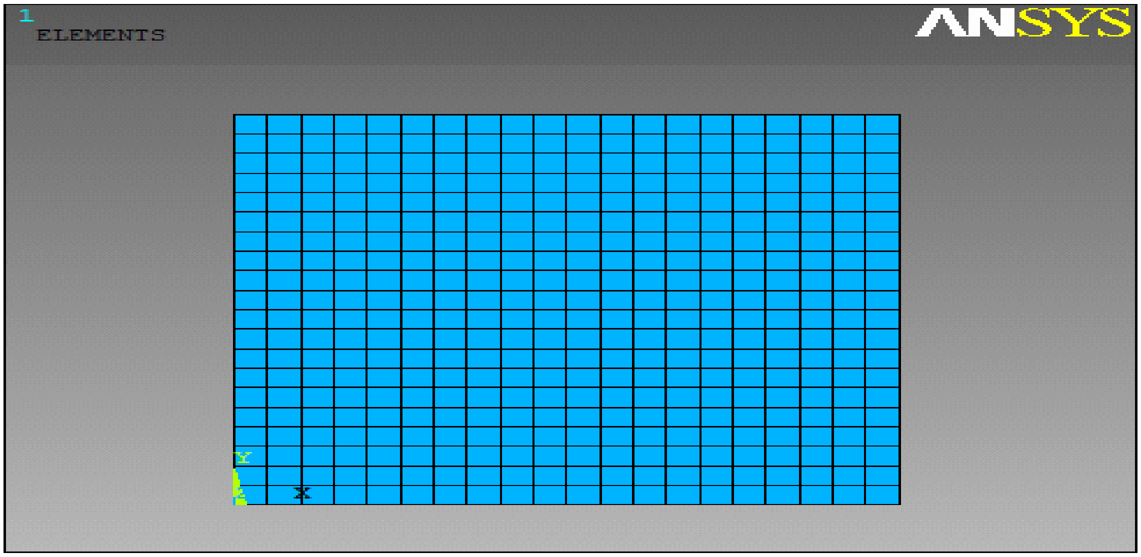


Fig. 3.12 A meshed rectangular section (100×100mm)

A rectangular section (100x100mm) with mapped meshing is shown in Fig. 3.12. It contains total 400 elements and has maximum 1281 number of nodes.

3.4.2.6 Boundary and loading condition: Boundary conditions and loads define the relationship of object with its surrounding. How objected is supported and what kind of loads are acting on system. . The boundary conditions are the degrees of freedom constraints necessary to hold the object in place in the environment. Loads are defined along the nodal coordinate directions upon the appropriate solid or finite element entities.

3.4.2.7 Solution

In this phase we perform the following operations-

- Specify the loads i.e. (point or pressure)
- Specify the constraints i.e. translational and rotational
- Finally the resulting set of equations are solved FEM software automatically generates matrices and computes the unknown displacement values.

3.4.2.8 Postprocessor

ANSYS results of entire model are reviewed in general post processor stage. It generally uses output parameters and has capabilities of-

- Listing the nodal displacements

- Deflection plots
- Plotting stress contour diagrams
- Tabular listing of complex data such as in load case combinations

3.5 Materials Used:

Graphite-Epoxy and Glass-Epoxy are two materials that are used for modeling and analysing the hybrid laminated structures. The mechanical properties and strength parameters for both materials are listed in tables below. The strength of Glass-Epoxy (1140 MPa) is less than the Graphite-Epoxy (1850 MPa) which means the Graphite-Epoxy lamina is stronger than Glass-Epoxy lamina.

a. Mechanical Properties of Graphite-Epoxy

Material	E_1(GPa)	E_2(GPa)	E_2(GPa)	ν_{12}	ν_{23}	G_{12}(GPa)
Graphite-Epoxy	126	11	11	0.28	0.4	6.6

Strength parameters for Graphite-Epoxy

X_t(MPa)	X_c(MPa)	Y_t(MPa)	Y_c(MPa)	S(MPa)
1950	-1480	48	-200	79

b. Mechanical Properties of Glass-Epoxy

Material	E_1(GPa)	E_2(GPa)	E_2(GPa)	ν_{12}	ν_{23}	G_{12}(GPa)
Glass-Epoxy	53.48	17.7	17.7	0.278	0.4	5.83

Strength parameters for Glass-Epoxy

X_t(MPa)	X_c(MPa)	Y_t(MPa)	Y_c(MPa)	S(MPa)
1140	-570	35	114	72

CHAPTER. 4 RESULTS AND DISCUSSION

4.1 Introduction

In the present investigation failure analysis of hybrid laminated composite structures has been performed for different stacking sequence and ply angle. Graphite-Epoxy and Glass-Epoxy are composite materials which have been used to make hybrid laminate. A rectangular plate under clamped-free and clamped-clamped configuration has been analysed. The laminated plate is made up of hybrid laminated of glass-epoxy and graphite epoxy lamina. In the present study We have calculated global stresses in X-direction, Y-direction and shear stress in XY-plane, also maximum deflection and failure index is calculated in different ply angle and stacking sequence system. Finite Element software ANSYS is used to model the hybrid rectangular laminate further, all values of stresses are represented graphically and necessary data has been tabulated below.

4.2 Validation of ANSYS model of laminates

Kam et al. in 1996 studied semi clamped graphite-epoxy laminated plate. The experimental results have been taken from their research paper and validated with finite element software ANSYS. The experimental result and ANSYS result shows close agreement. The results have been tabulated below.

Table 4.1 Comparison of ANSYS results with experimental data (Kam, 1996) for $(0^{\circ}_2/90^{\circ}_2)_s$ laminate

Failure Criteria	First Ply Failure Load(N)		Discrepancy %
	ANSYS	Experimental	
Max. stress	225.63	253	11.03
Tsai-Wu	274.30		8.16

Table 4.2 Comparison of ANSYS results with experimental data for $(0^\circ/90^\circ/0^\circ/90^\circ)_s$ laminate

Failure Criteria	First Ply Failure Load(N)		Discrepancy%
	ANSYS	Experimental	
Max. stress	281.77	317.74	11.32
Tsai-Wu	301.70		5.05

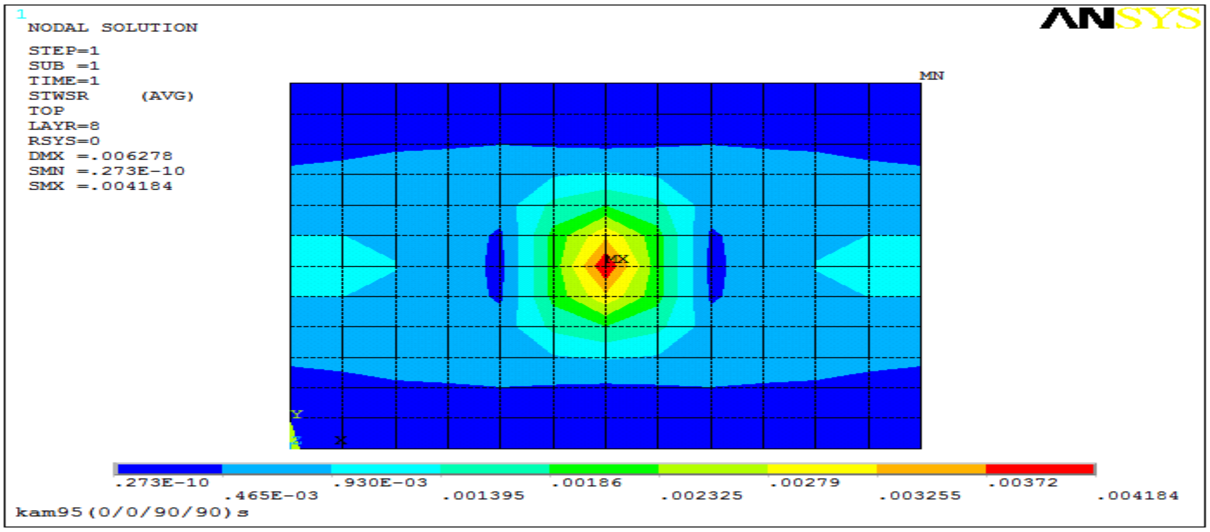


Figure 4.1 Tsai-Wu failure index plot for $(0^\circ_2/90^\circ_2)_s$ laminate

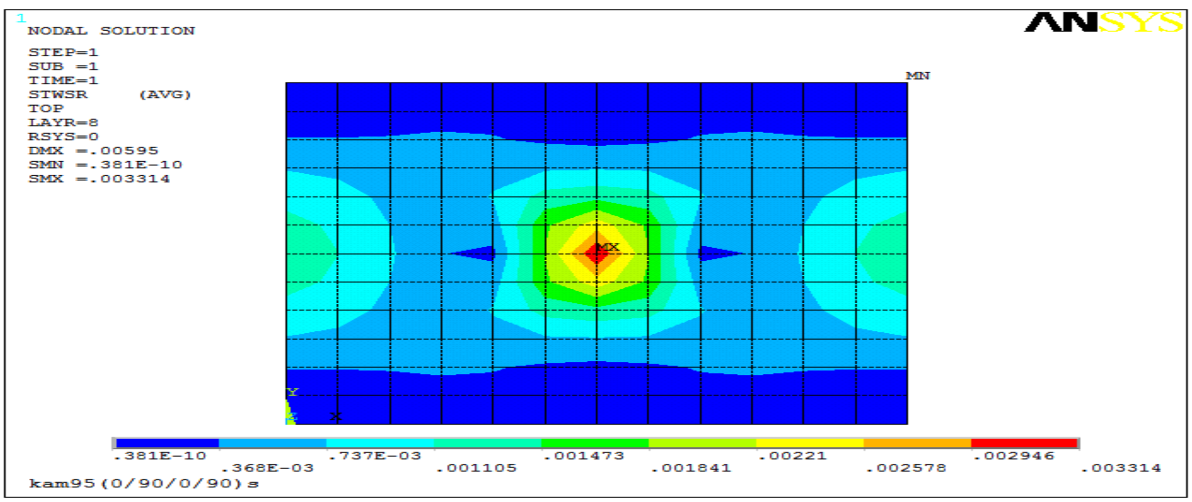


Figure 4.2 Tsai-Wu failure index plot for $(0^\circ/90^\circ/0^\circ/90^\circ)_s$ laminate

4.3. A parametric study of hybrid laminated composite plate

We have taken two types of lamina graphite epoxy and glass epoxy. Graphite epoxy lamina and Glass epoxy lamina have been indicated by material ID1 and ID 2 respectively.

Table4.3 A parametric study of hybrid laminated composite plate involving stacking sequence, ply orientation and number of lamina have been studies

Ply Orientation	Angle ply
	Cross ply
	General ply
	Quasi-isotropic ply
	Unidirectional ply
Stacking Sequence (8 layers)	1-2-1-2-1-2-1-2
	2-2-2-2-1-1-1-1
	1-1-1-1-2-2-2-2
	1-1-2-2-2-2-1-1
	2-2-1-1-1-1-2-2
	1-1-2-2-1-1-2-2
	2-2-1-1-2-2-1-1
	1-2-2-1-1-2-2-1
	2-1-1-2-2-1-1-2
Stacking Sequence(4 layers)	1-2-1-2
	1-1-2-2
	2-2-1-1
	1-2-2-1
	2-1-1-2
Number of Lamina	8
	4

The general methodology is to choose a stacking sequence and then analysed all the five orientations. Thus there will be firstly (8×5) analyses for 8 layer stacking sequence and twenty five (5×5) for 4 layer stacking. Table 4.3 depicts three parameter ply orientation, stacking sequence and number of lamina. A hybrid laminated composite structure is modelled in ANSYS. First of all we take 8 layers of lamina then 4 layers of lamina to study clamped-clamped configuration and clamped free configuration. After that we vary stacking sequence and ply angle system and study the failure stress index and deflection under 100 N loads. The first material ID1 denotes Graphite- Epoxy lamina while second material ID2 denotes Glass-

Epoxy lamina. The dimensions of plate are (100×50×1.2) mm. The dimensions of plate remain same in each analysis. We have only varied angle system, stacking sequence and number of lamina.

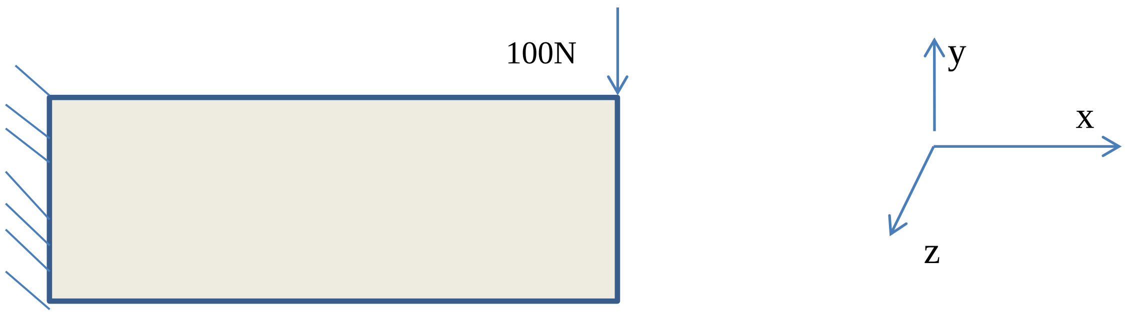


Figure. 4.3 A rectangular hybrid laminate subjected transverse load

4.4 Plate in clamped-free configuration subjected to transverse loading

The global stress in X direction, Y direction, and shear stress in XY plane is tabulated. Also deflection and failure indices of various stacking sequence and angle ply system is listed.

4.4.1 Study of plate in clamped –free configuration for 8 layers

Table: 4.4 Stacking sequence of 1-2-1-2-1-2-1-2 of clamped free configuration

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.315	11.675	16.598	0.4590	0.4408	0.3844
Cross ply	53.272	3.3677	5.117	0.1140	0.1389	0.1906
General ply	70.865	2.4485	4.033	0.3936	0.4213	0.2597
Quasi isotropic	78.302	4.1919	3.022	0.2301	0.2530	0.1684
Unidirectional	41.102	6.8717	3.903	0.6124	0.6388	0.1179

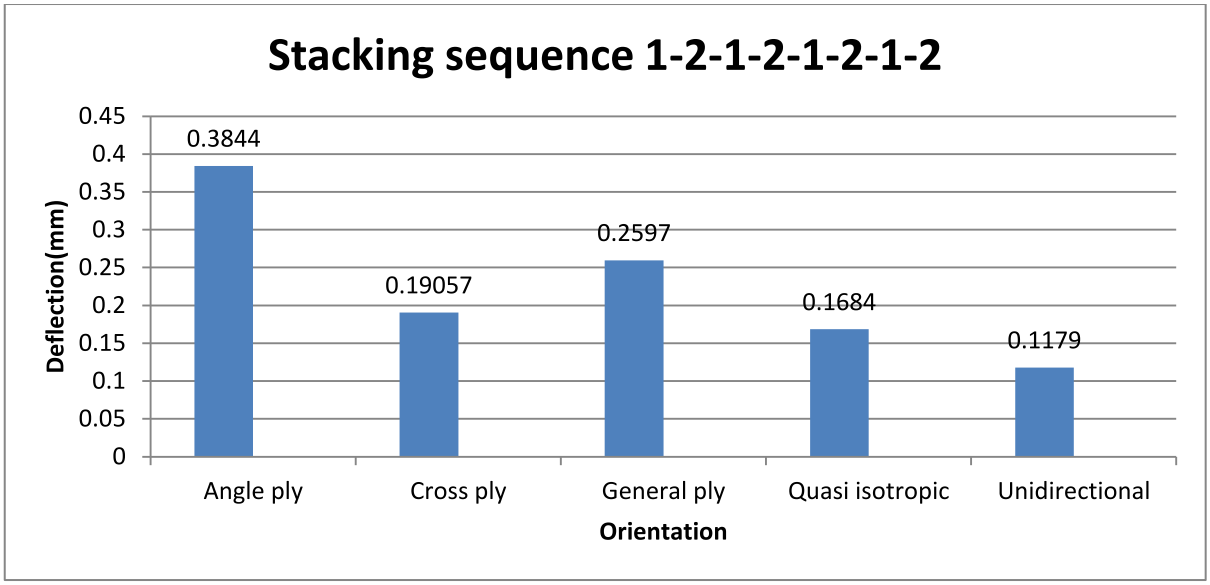


Figure 4.4 Deflection of plate under different ply angle

From Table 4.4 and it can be observed that the deflection is minimum in unidirectional fibres. Which means unidirectional fibres shows maximum stiffness and angle ply shows minimum stiffness. So where we need more stiffness we used unidirectional fibres. Now looking at failure index, unidirectional fibres have more chance to fail, while cross ply have less chance to fail. So where we need large factor of safety we should use cross ply.

Clamped free configuration having upper fibre from neutral axis to material ID1 and bottom fibres have material ID 2 and vice versa

For hybrid laminate, the value of global stress has been tabulated below in table4.5a and Table4.5b. In this stacking sequence general ply shows minimum deflection of 0.1019mm while unidirectional shows maximum deflection of 0.3664mm. If stacking sequence is reversed then deflection and global stresses are unchanged. However failure index has been changed. When material ID1 is above the mid plane it shows minimum failure index corresponding ply angle. The maximum strength corresponds to quasi- isotropic orientation.

Table 4.5a Stress distribution and deflection in stacking sequence 2-2-2-2-1-1-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.127	12.8512	18.548	0.4532	0.4364	0.2143
Cross ply	57.343	3.3287	4.521	0.1690	0.1364	0.1407
General ply	85.706	3.456	2.8948	0.1544	0.1756	0.1018
Quasi isotropic	90.861	3.7578	2.1548	0.0766	0.1061	0.1222
Unidirectional	39.263	6.9074	5.8554	0.3491	0.3491	0.3664

Table 4.5b Stress distribution and deflection in stacking sequence 1-1-1-1-2-2-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.127	12.851	18.548	0.4887	0.4734	0.2143
Cross ply	57.343	3.3287	4.521	0.2614	0.3073	0.1407
General ply	85.706	3.456	2.8948	0.4092	0.4302	0.10185
Quasi isotropic	90.861	3.7578	2.1548	0.2670	0.2985	0.1222
Unidirectional	39.263	6.9074	5.8554	0.51287	0.5371	0.3664

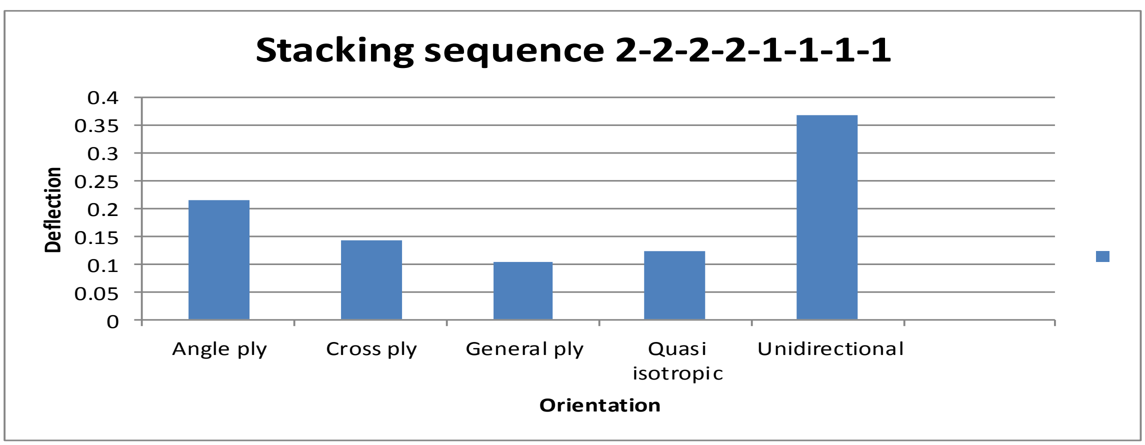


Figure 4.5 Deflection of plate under different ply angle

Table 4.6 Stress distribution and deflection in stacking sequence 1-1-2-2-2-2-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.372	16.203	20.036	0.5369	0.5235	0.1852
Cross ply	59.122	2.0975	3.4988	0.1932	0.1587	0.1134
General ply	111.034	1.4608	1.935	0.1466	0.1731	0.100
Quasi isotropic	109.465	1.5	1.0455	0.1029	0.1376	0.100
Unidirectional	41.8965	4.198	3.723	0.2808	0.2966	0.1150

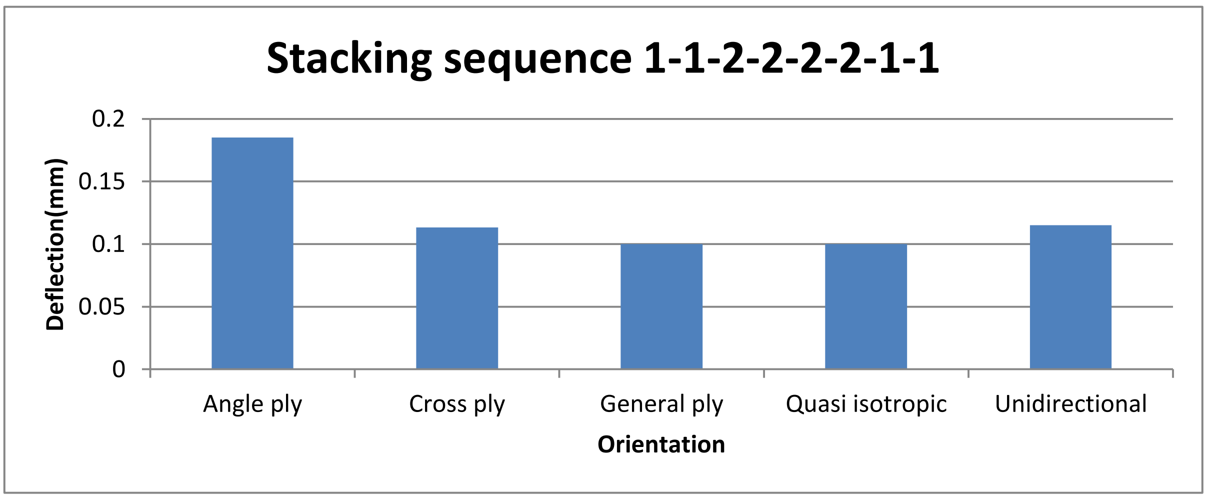


Figure 4.6 Deflection of plate under different ply angle

From **Table 4.6** it is found that the deflection in general ply and quasi isotropic system is same. But the failure index is different. The failure index is minimum for quasi- isotropic angle system. And both the failure indices Maximum stress and Tsai-Wu index are close agreement. So our best choice in this system is quasi-isotropic angle system.

Table 4.7 Stress distribution and deflection in stacking sequence 2-2-1-1-1-1-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	18.5024	5.922	7.4057	0.5194	0.4948	0.1849
Cross ply	25.4937	3.423	3.889	0.1917	0.2363	0.1114
General ply	37.2559	2.378	1.709	0.4224	0.4352	0.1001
Quasi isotropic	46.136	3.446	2.424	0.2130	0.2361	0.1361
Unidirectional	19.1919	6.879	3.284	0.6475	0.6745	0.1147

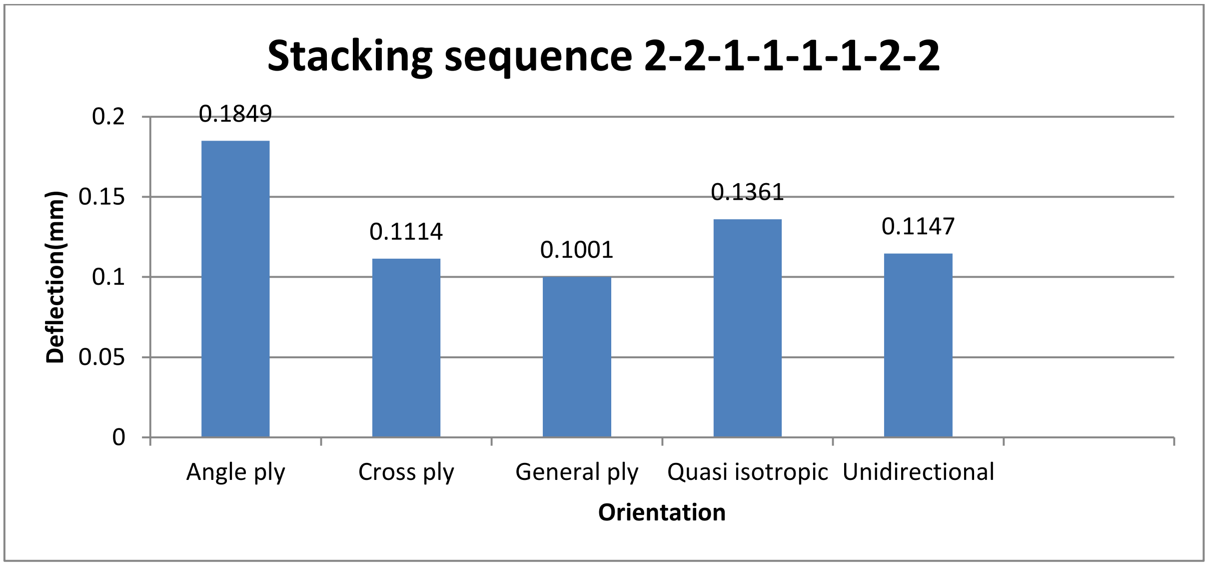


Figure 4.7 Deflection plate under different ply angle

From above table it has been concluded that the minimum deflection is for general ply angle system which is 0.1001 mm so general ply angle system shows maximum stiffness. So it is our choice where we need minimum deflection. If we consider strength then we see that cross ply has minimum failure index means it shows less chance to fail. So cross ply angle system shows maximum strength.

Table 4.8 Stress distribution and deflection in stacking sequence 2-2-1-1-2-2-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.49	14.926	19.578	0.5438	0.5292	0.1856
Cross ply	58.847	3.4122	4.324	0.1697	0.1382	0.1143
General ply	104.22	3.1764	2.4388	0.1488	0.1741	0.103
Quasi isotropic	100.96	3.90	2.03	0.09232	0.1242	0.1763
Unidirectional	40.391	6.866	4.528	0.3148	0.3297	0.1263

Table 4.9 Stress distribution and deflection in stacking sequence 1-1-2-2-1-1-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.49	14.926	19.578	0.5129	0.4910	0.1856
Cross ply	58.847	3.4122	4.324	0.2404	0.2868	0.1143
General ply	104.221	3.1764	2.4388	0.4205	0.4357	0.103
Quasi isotropic	100.96	3.90	2.03	0.2251	0.2525	0.1763
Unidirectional	40.3911	6.866	4.528	0.5781	0.6037	0.1263

From the above table it has been concluded that both the stacking sequence shows same deflection corresponding angle system. The only difference in failure index, the minimum failure index shows among both of them stacking sequence is 0.092 for quasi isotropic angle system. So quasi-isotropic angle system is safer than all other ply angle system. General ply angle system shows stiffer because it shows minimum deflection among all the stacking sequence.

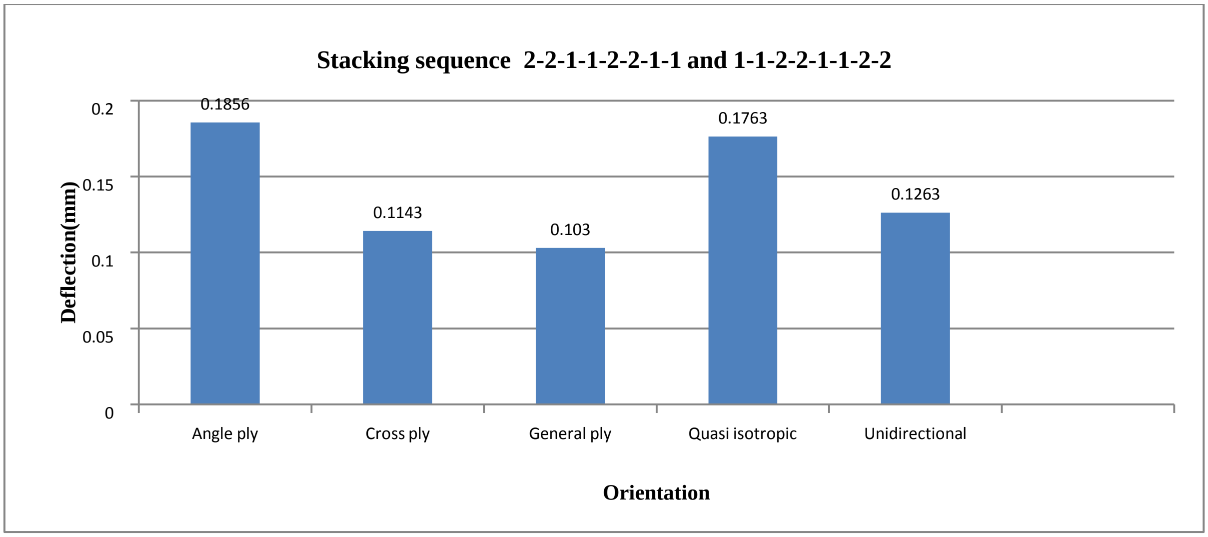


Figure 4.8 Deflection of plate under different ply angle

Table 4.10 Stress distribution and deflection in stacking sequence 1-2-2-1-1-2-2-1

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.916	16.214	20.0437	0.5363	0.5229	0.1850
Cross ply	59.122	2.098	3.499	0.1932	0.1587	0.1113
General ply	110.98	1.4618	1.935	0.1465	0.1731	0.100
Quasi isotropic	70.459	1.9612	2.226	0.1160	0.1205	0.1286
Unidirectional	41.8873	4.201	3.718	0.2805	0.2962	0.1147

Table 4.11 Stress distribution and deflection in stacking sequence 2-1-1-2-2-1-1-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	18.5041	5.912	7.402	0.5202	0.4955	0.1851
Cross ply	25.4941	3.417	3.087	0.1919	0.2364	0.1115
General ply	37.2853	2.3750	1.7096	0.4227	0.4355	0.100
Quasi isotropic	63.9781	1.898	1.312	0.2951	0.3226	0.1286
Unidirectional	19.1925	6.878	3.285	0.6447	0.6747	0.1147

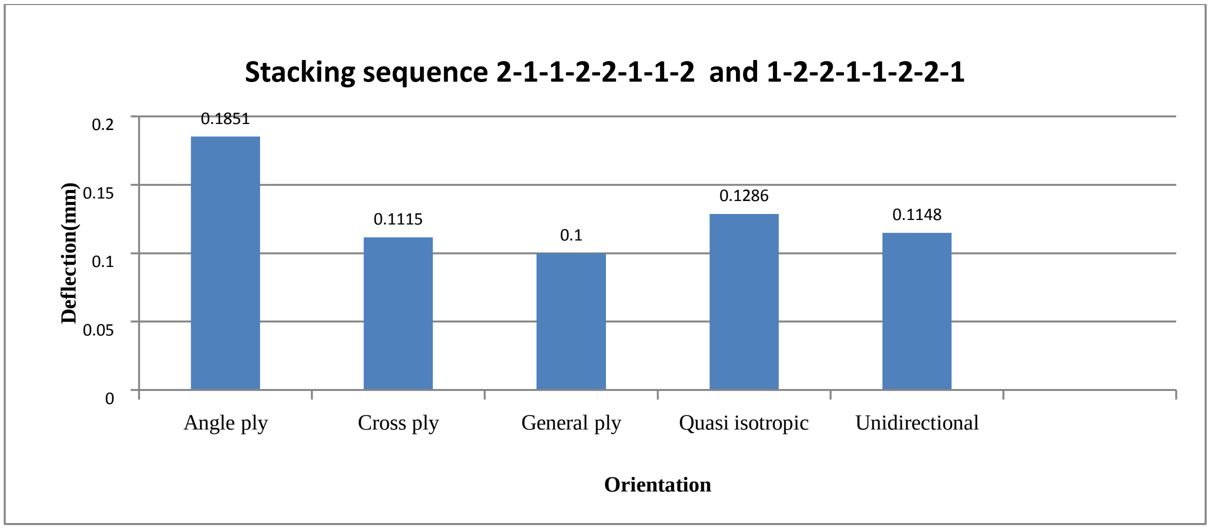


Figure 4.9 Deflection of plate under different ply angle

From the above table it has been concluded that both the stacking sequence are symmetry in respect to deflection angle. And minimum deflection is shows for general ply angle system which has 0.1 mm. And minimum failure index shows for quasi-isotropic material system. So where we need strength criteria we used quasi isotropic material system.

4.5 Study of clamped –free configuration for 4 layers

Now we are changing number of lamina keeping overall constant thickness and the global stress in X, Y, direction and Shear stress in XY plane is tabulated. Also deflection and failure index is listed of various stacking sequence and orientation

Table 4.12 Stress distribution and deflection in stacking sequence 1-2-1-2

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	28.33	11.608	16.483	0.6024	0.5788	0.3867
Cross ply	53.9298	3.4044	5.095	0.2669	0.2182	0.1995
General ply	73.944	2.0018	5.326	0.1791	0.2062	0.2838
Quasi isotropic	54.087	16.769	6.141	0.3330	0.3614	0.2375
Unidirectional	40.3911	6.866	4.528	0.5781	0.6037	0.1263

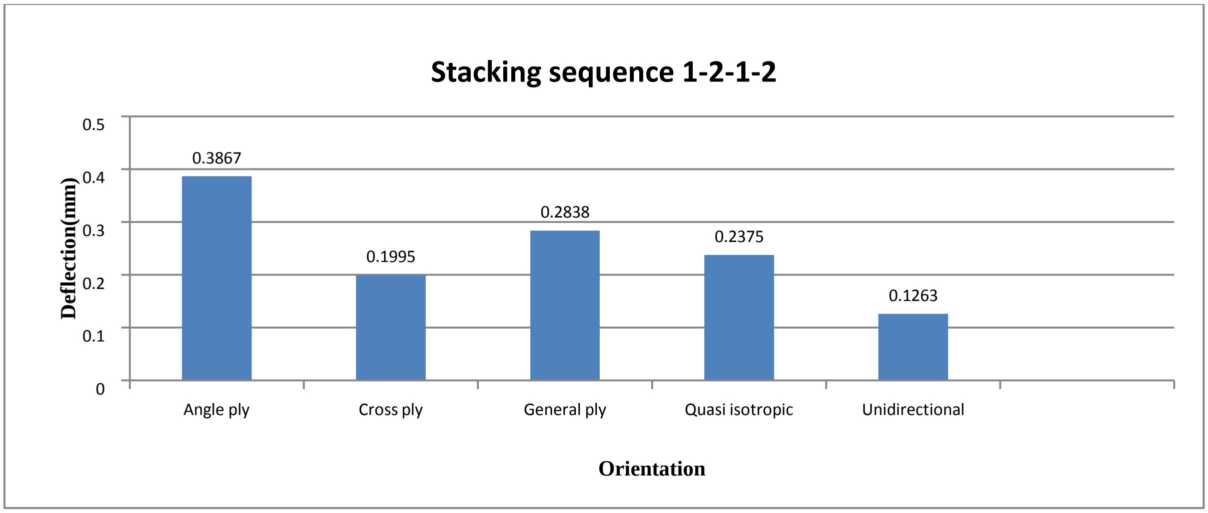


Figure 4.10 Deflection of plate under different ply angle

Table 4.13 Stress distribution and deflection in stacking sequence 2-2-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	27.926	12.0166	17.941	0.5778	0.5563	0.2459
Cross ply	56.684	2.962	4.060	0.18635	0.1503	0.1612
General ply	80.076	3.105	2.045	0.1591	0.1773	0.1297
Quasi isotropic	45.281	20.2851	8.8355	0.2622	0.2818	0.4995
Unidirectional	39.263	6.9074	5.835	0.3491	0.3664	0.1566

Table 4.14 Stress distribution and deflection in stacking sequence 1-1-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	27.926	12.0166	17.941	0.4787	0.4722	0.2459
Cross ply	56.684	2.962	4.060	0.2484	0.2897	0.1612
General ply	80.076	3.105	2.045	0.3943	0.4163	0.1297
Quasi isotropic	45.281	20.2851	8.8355	0.3261	0.3521	0.4995
Unidirectional	39.263	6.9074	5.835	0.5128	0.5371	0.1566

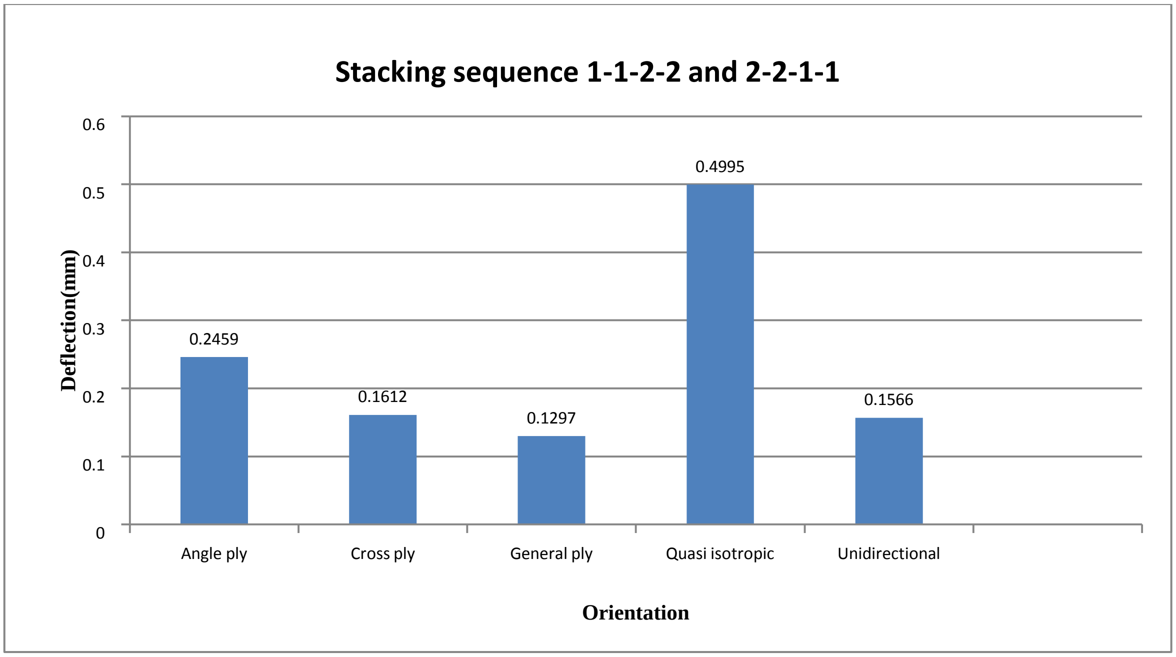


Figure 4.11 Deflection of plate under different ply angle

Table 4.15 Stress distribution and deflection in stacking sequence 1-2-2-1

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	23.722	10.888	14.098	0.5380	0.5233	0.18766
Cross ply	44.979	2.645	3.698	0.2268	0.19299	0.1036
General ply	79.3861	2.645	3.698	0.1721	0.1951	0.0958
Quasi isotropic	52.9808	18.978	9.899	0.3800	0.4116	0.3448
Unidirectional	41.896	4.198	3.723	0.2808	0.2966	0.1150

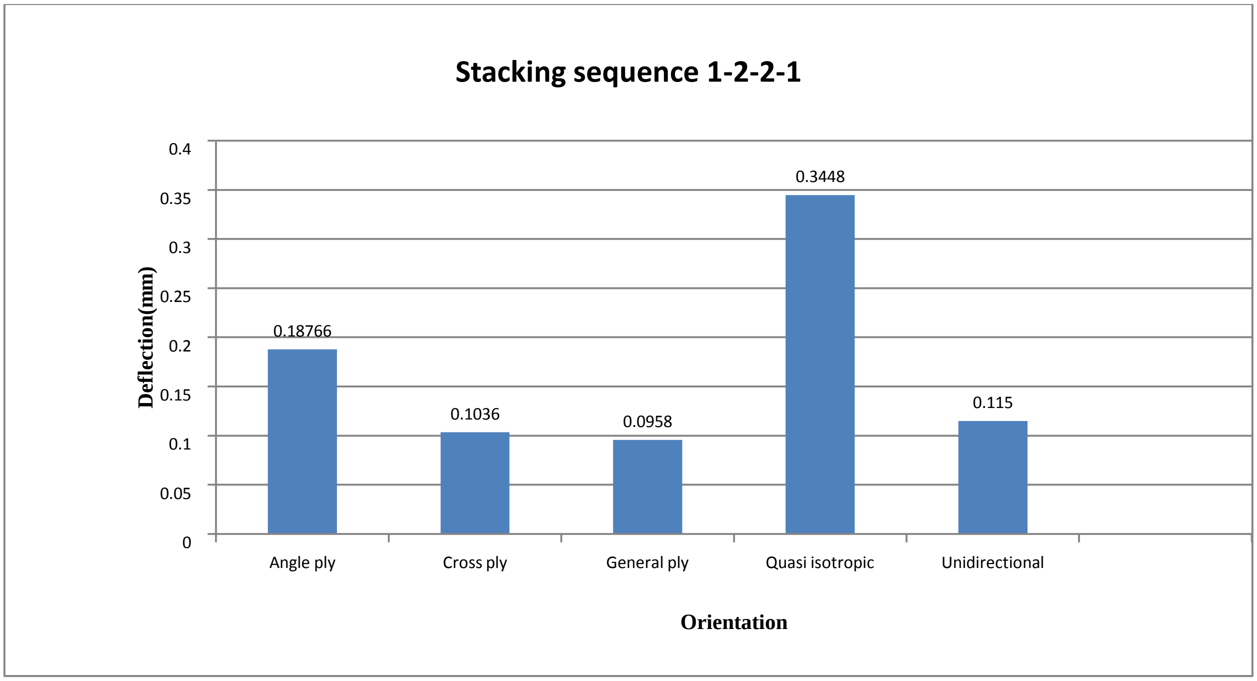


Figure 4.12 Deflection of plate under different ply angle

Table 4.16 Stress distribution and deflection in stacking sequence 2-1-1-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	22.135	11.191	12.4007	0.5176	0.4908	0.1957
Cross ply	38.782	3.245	2.872	0.1609	0.1832	0.1409
General ply	60.6517	2.253	2.246	0.3913	0.4132	0.1233
Quasi isotropic	61.8516	8.089	3.655	0.5683	0.6679	0.3287
Unidirectional	19.1919	6.879	3.2284	0.6475	0.6745	0.1147

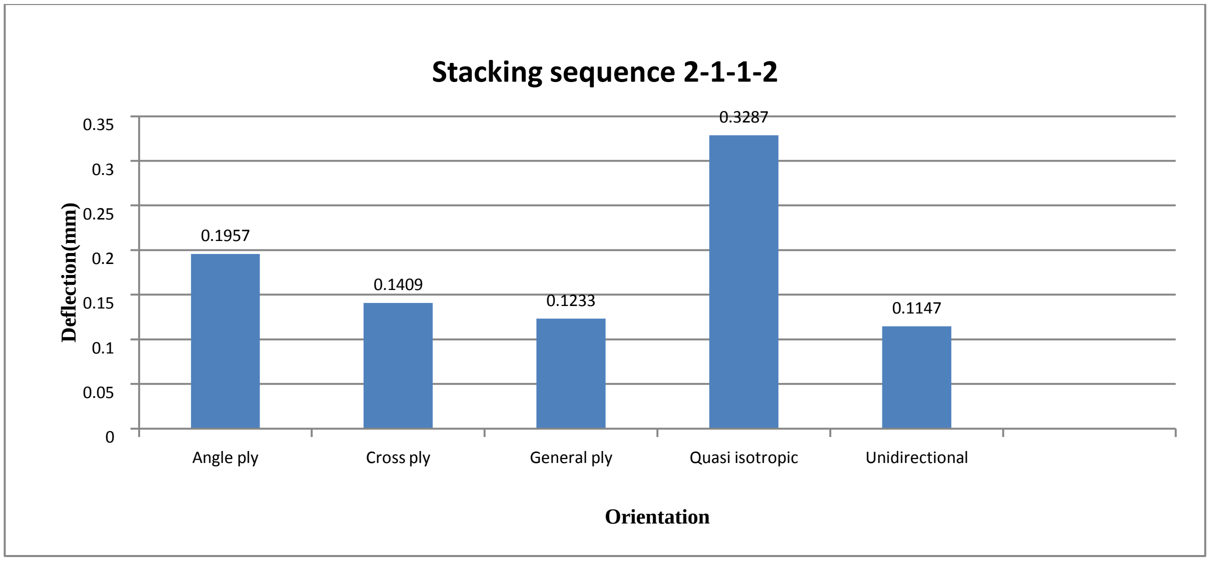


Figure 4.13 Deflection of plate under different ply angle

Now we decrease the number of lamina to four and the stacking sequence is vary same as vary previously. By comparing same stacking sequence with eight layer of lamina we found that the deflection in four layer stacking sequence system is more. So increasing number of layer is beneficial. But the failure index is increased in eight layer system. That means when we increased number of lamina then strength decrease but stiffness increases.

4.5 Now study of clamped –clamped configuration

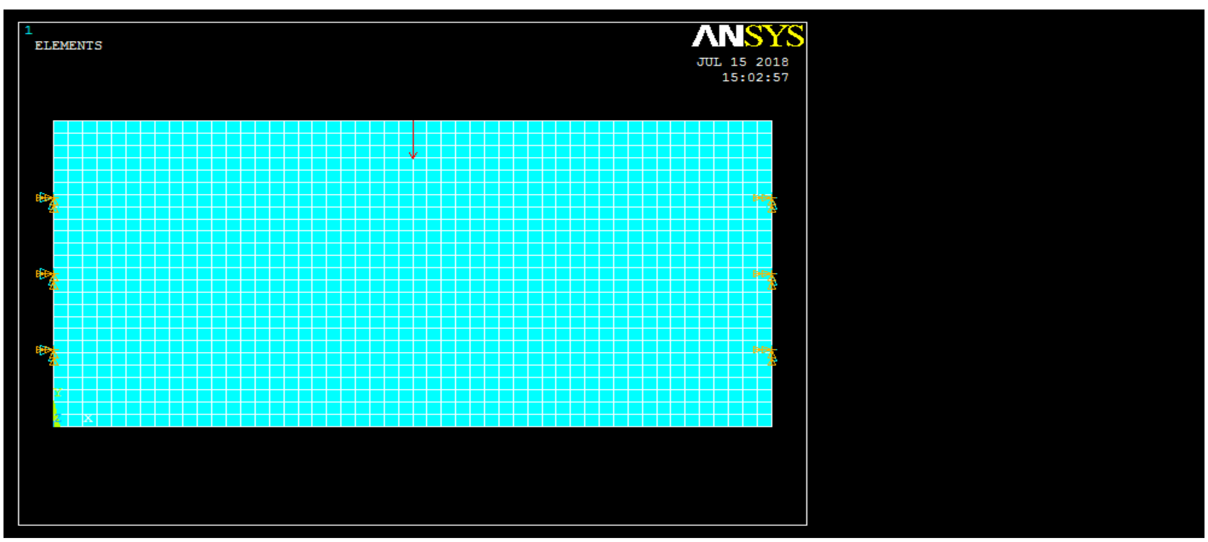


Figure 4.14 Clamped- Clamped configuration of plate

Table 4.17 Stress distribution and deflection in stacking sequence 1-2-1-2-1-2-1-2

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	7.701	1.952	8.273	0.2631	0.2579	.0257
Cross ply	9.408	.5146	6.408	0.0635	0.0594	.02599
General ply	6.482	1.525	6.578	0.1740	0.1762	.02313
Quasi isotropic	8.767	1.0929	2.808	0.0837	0.0810	.0157
Unidirectional	4.490	2.5088	3.027	0.0719	0.0753	.0134

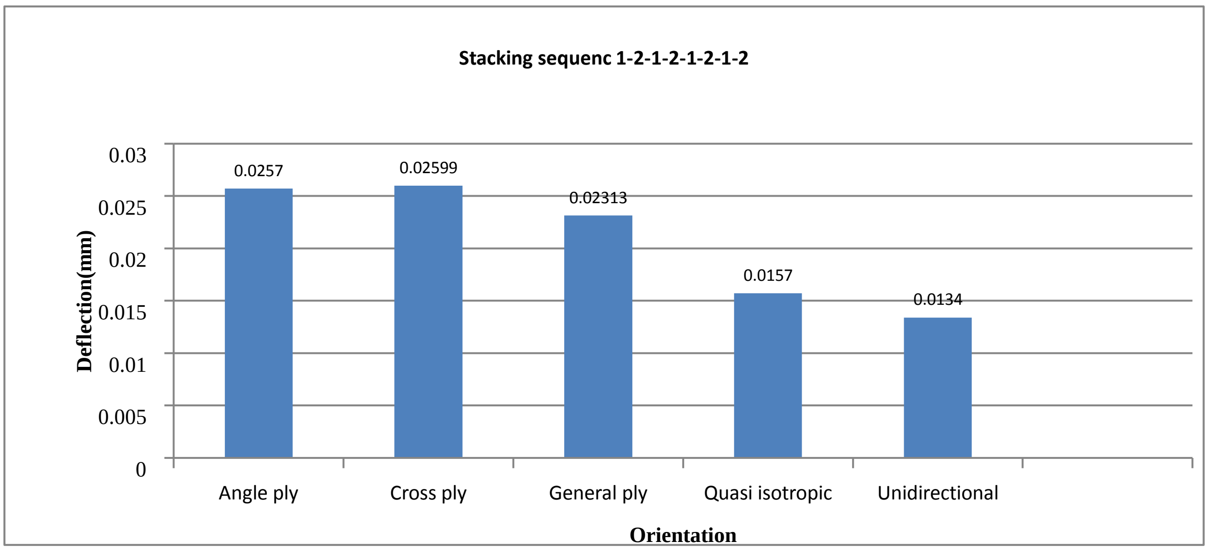


Figure 4.15 Deflection of plate under different ply angle

From the above table it has been conclude that the deflection in minimum in unidirectional ply system. And the failure index is minimum for cross ply angle system. So if we need more stiff then unidirectional fibre is used. But the cross plies shows more safe among all the ply angle system**.**

Table 4.18 Stress distribution and deflection in stacking sequence 2-2-2-2-1-1-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.546	3.0354	3.3054	0.0550	0.0437	0.01993
Cross ply	10.668	.7452	4.917	0.0564	0.0483	0.0174
General ply	8.0239	1.753	5.875	0.07494	0.0805	0.0168
Quasi isotropic	11.138	.8022	2.934	0.0271	0.0234	0.0149
Unidirectional	6.635	2.159	9.350	0.1249	0.1199	0.0287

Table 4.19 Stress distribution and deflection in stacking sequence 1-1-1-1-2-2-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.546	3.0354	3.3054	0.0943	0.1081	0.01993
Cross ply	10.668	.7452	4.917	0.1257	0.1221	0.0174
General ply	8.0239	1.753	5.875	0.1903	0.1901	0.016
Quasi isotropic	11.138	.8022	2.934	0.1267	0.1246	0.0149
Unidirectional	6.635	2.159	9.350	0.2167	0.2118	0.0287

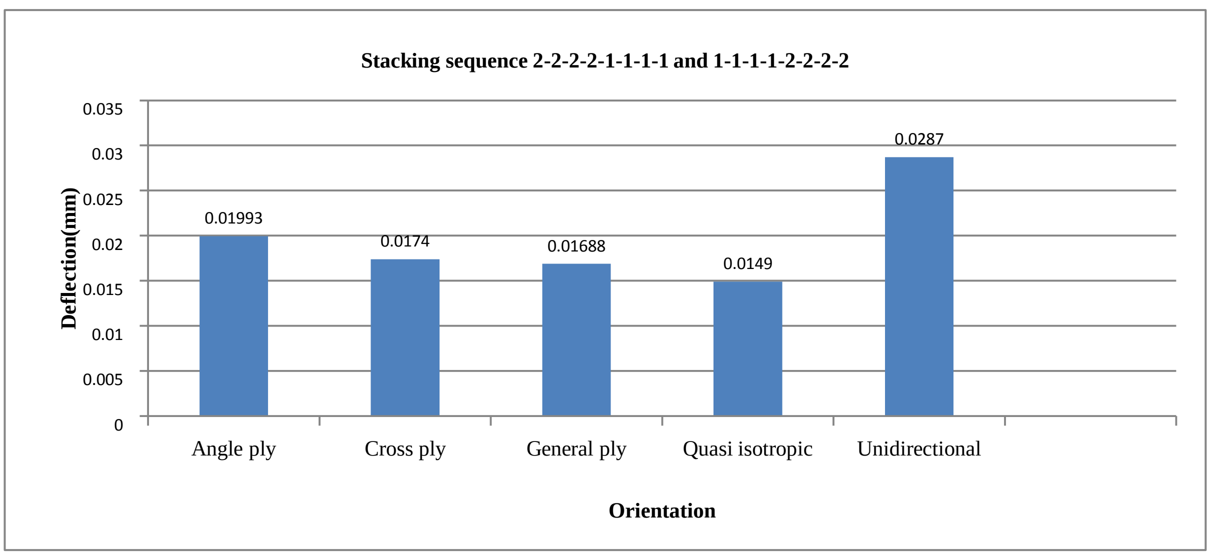


Figure 4.16 Deflection of plate under different ply angle

For hybrid laminate, the value of global stress has been tabulated below in table 4.18 and table 4.19. In this sacking sequence quasi-isotropic shows minimum deflection of 0.0149mm while unidirectional ply shows maximum deflection of 0.0287mm. If stacking sequence is reverse then deflection and global stress unchanged. In this symmetry deflection is same but failure index has been changed. When material ID1 is above the neutral plane it shows minimum failure index corresponding ply angle. The maximum strength shows qusi isotropic orientation.

Table 4.20 Stress distribution and deflection in stacking sequence 1-1-2-2-2-2-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	3.870	2.190	2.723	0.0706	0.0566	0.0123
Cross ply	11.6245	.3510	4.807	0.0608	0.05144	0.0172
General ply	8.239	1.228	5.776	0.0731	0.0749	0.0167
Quasi isotropic	9.198	.7644	3.535	0.0451	0.0434	0.0130
Unidirectional	8.1048	1.146	7.924	0.100	0.0924	0.02559

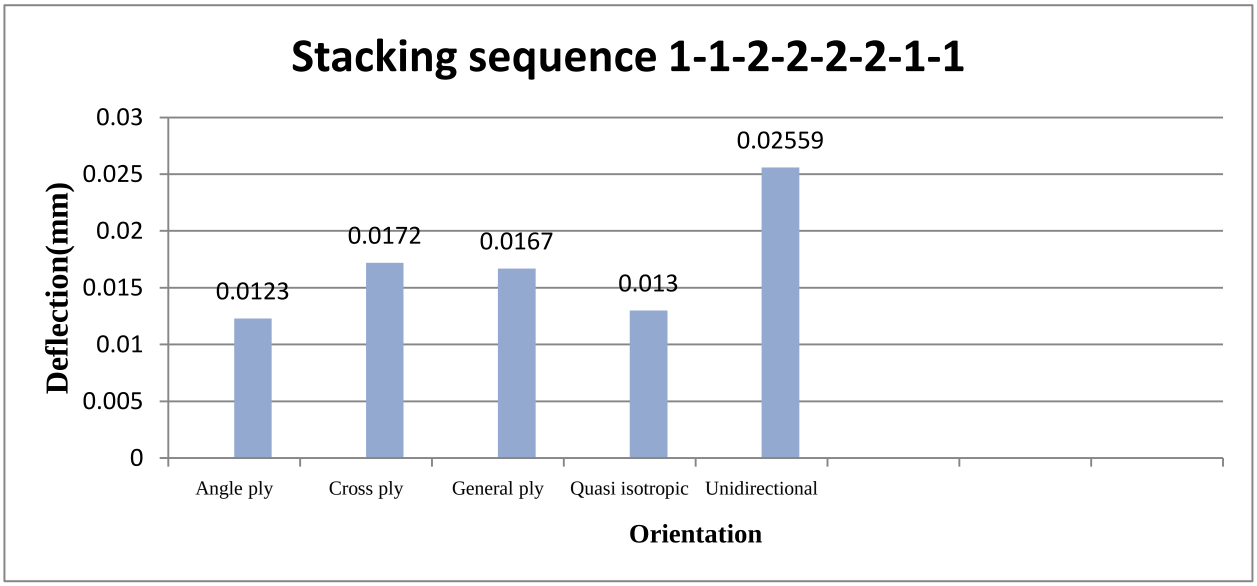


Figure 4.17 Deflection of plate under different ply angle

From above chart it has been concluded that deflection of unidirectional fibre is maximum, means it shows less stiffness. And the deflection of angle ply is minimum, so angle ply shows maximum stiffness among them. Quasi isotropic angle system shows minimum failure index means it is safer among all the angle ply system.

Table 4.21 Stress distribution and deflection in stacking sequence 2-2-1-1-1-1-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	2.253	1.628	1.629	0.0743	0.0838	0.01226
Cross ply	4.995	.576	4.245	0.0966	0.0929	0.01728
General ply	3.469	2.0135	5.101	0.2018	0.2012	0.0167
Quasi isotropic	5.919	.777	1.752	0.0889	0.860	0.0116
Unidirectional	3.472	1.885	6.999	0.2795	0.2741	0.0255

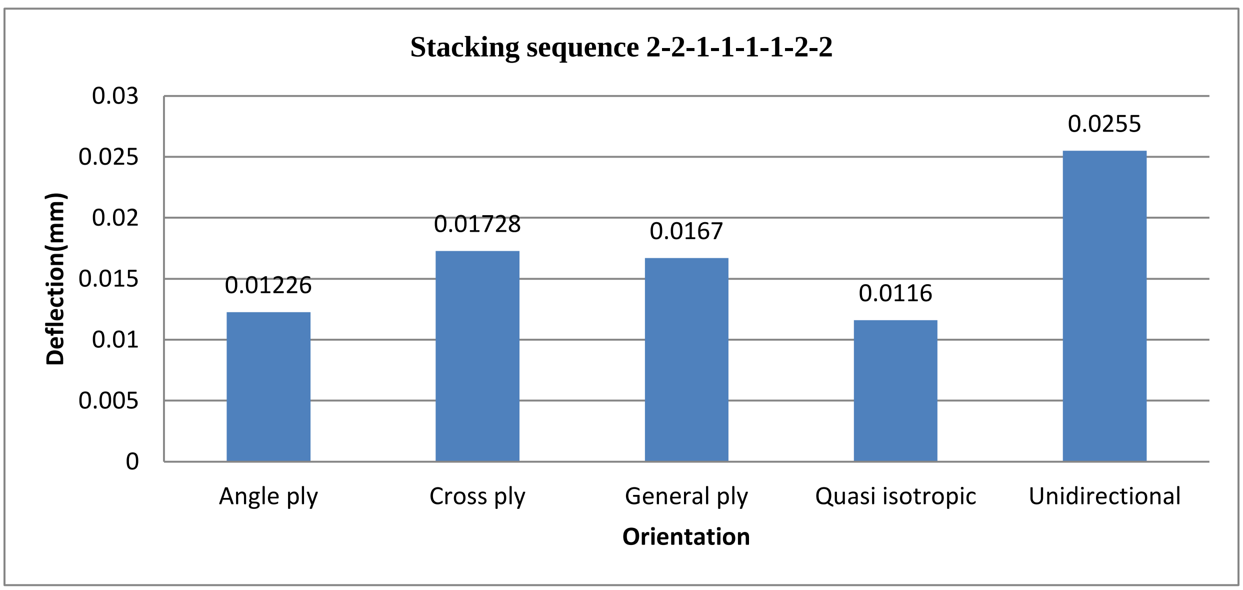


Figure 4.18 Deflection of plate under different ply angle

From the above table and chart it can be observed that the deflection for quasi-isotropic angle system has minimum whereas unidirectional angle system has maximum deflection. The maximum stress index and Tsai-Wu index is minimum for angle ply system. So angle ply shows maximum stiffness among all of the ply angle system

Table 4.22 Stress distribution and deflection in stacking sequence 2-2-1-1-2-2-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.124	2.512	2.881	0.0626	0.05039	0.0143
Cross ply	11.3811	.7033	4.774	0.569	0.0481	0.0174
General ply	8.0341	1.930	5.729	0.0725	0.0771	0.017
Quasi isotropic	9.578	.8384	3.224	0.0408	0.0381	0.0127
Unidirectional	7.328	2.0178	8.622	0.1101	0.1051	0.02637

Table 4.23 Stress distribution and deflection in stacking sequence 1-1-2-2-1-1-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.124	2.512	2.881	0.0856	0.0981	0.0143
Cross ply	11.3811	.7033	4.774	0.1170	0.1134	0.0174
General ply	8.0341	1.930	5.729	0.1999	0.1991	0.017
Quasi isotropic	9.578	.8384	3.224	0.0895	0.0873	0.0127
Unidirectional	7.328	2.0178	8.622	0.2471	0.2420	0.0263

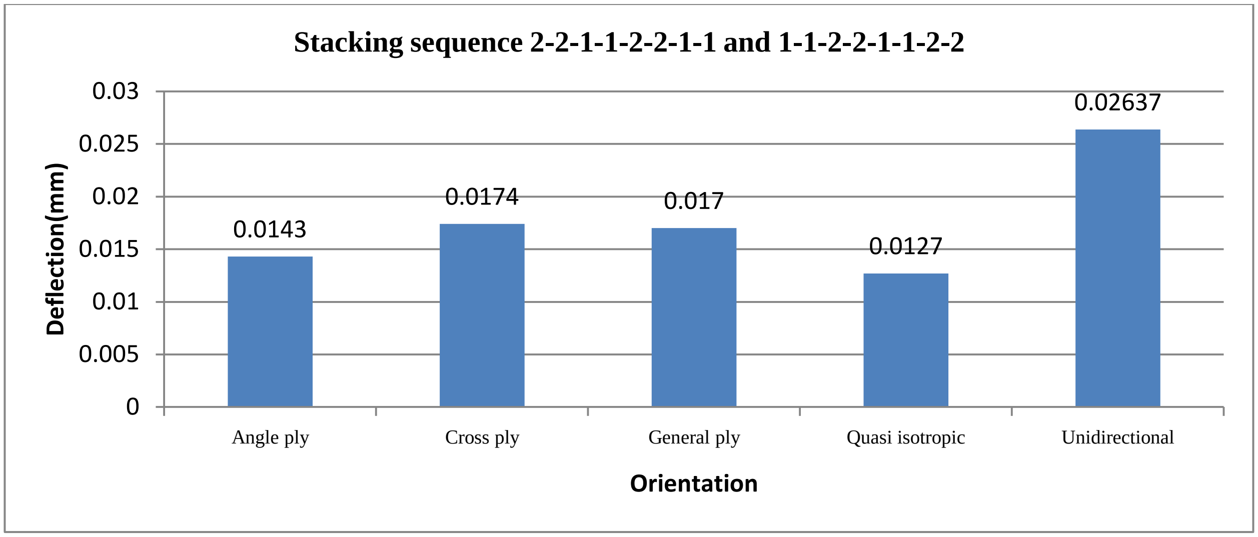


Figure 4.19 Deflection of plate under different ply angle

From above table 4.19 and table 4.20 it can be observed that both the stacking sequence shows same deflection to corresponding angle system it means both stacking sequence has same stiffness to corresponding angle system. They are symmetry in respect to stiffness. But the Failure index has been changed that means its strength changed. From above table it can been seen that quasi-isotropic and angle ply shows almost same failure index which is minimum among them. So angle ply and quasi isotropic is good in respect to strength.

Table 4.21 Stress distribution and deflection in stacking sequence 1-2-2-1-1-2-2-1

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	3.872	2.190	2.726	0.0706	0.0566	0.01228
Cross ply	11.624	.3512	4.807	0.0608	0.05144	0.01724
General ply	8.239	1.228	5.777	0.0731	0.07488	0.01669
Quasi isotropic	10.637	.4430	3.111	0.039	0.0313	0.0193
Unidirectional	8.1045	1.147	7.924	0.1003	0.0922	0.0255

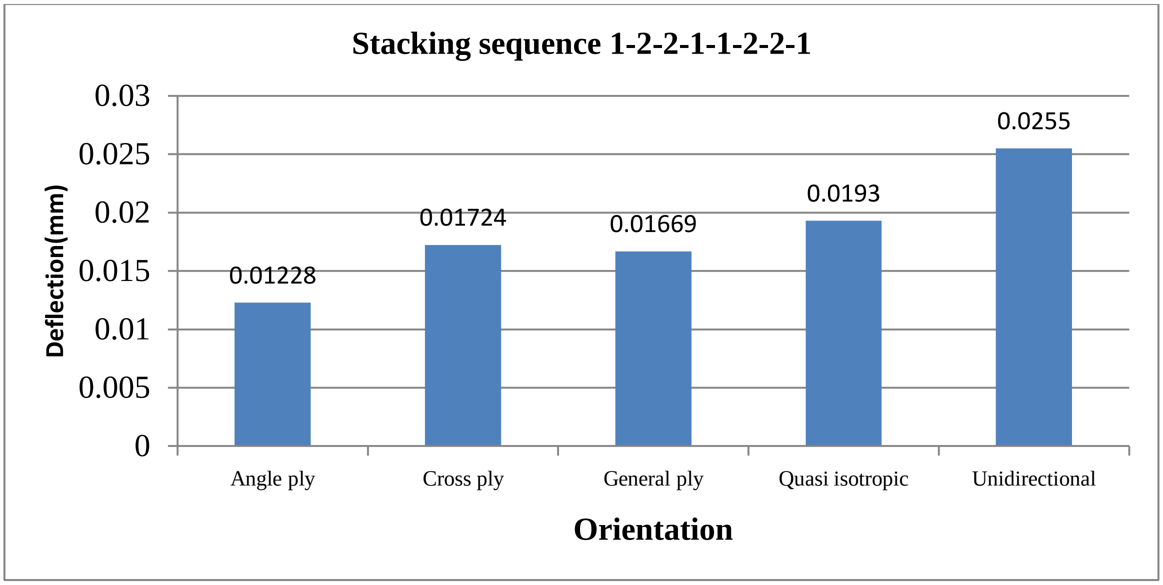


Figure 4.20 Deflection of plate under different ply angle

From above table 4.21 it can be observed that angle ply shows minimum deflection. it means this angle system has maximum stiffness among all the ply angle system. But the failure index is minimum for quasi-isotropic angle ply system. So quasi-isotropic shows maximum strength. So where we need stiffer arrangement we will use angle ply. And where we need maximum strength we will use quasi- isotropic angle system.

Table 4.24 Stress distribution and deflection in stacking sequence 2-1-1-2-2-1-1-2-2

Orientation	**Global Stress(MPa)**			**Failure index**		**Deflection (mm)**
	X	**Y**	**XY**	**Maximum Stress**	**Tsai Wu**	
Angle ply	2.225	1.626	1.629	0.0744	0.0839	0.0123
Cross ply	4.995	.574	4.24	0.0167	0.0930	0.0173
General ply	3.47	2.0118	5.099	0.2020	0.2013	0.0167
Quasi isotropic	5.264	1.170	1.861	0.1067	0.1044	0.01136
Unidirectional	3.4727	1.884	6.99	0.2795	0.2742	0.0255

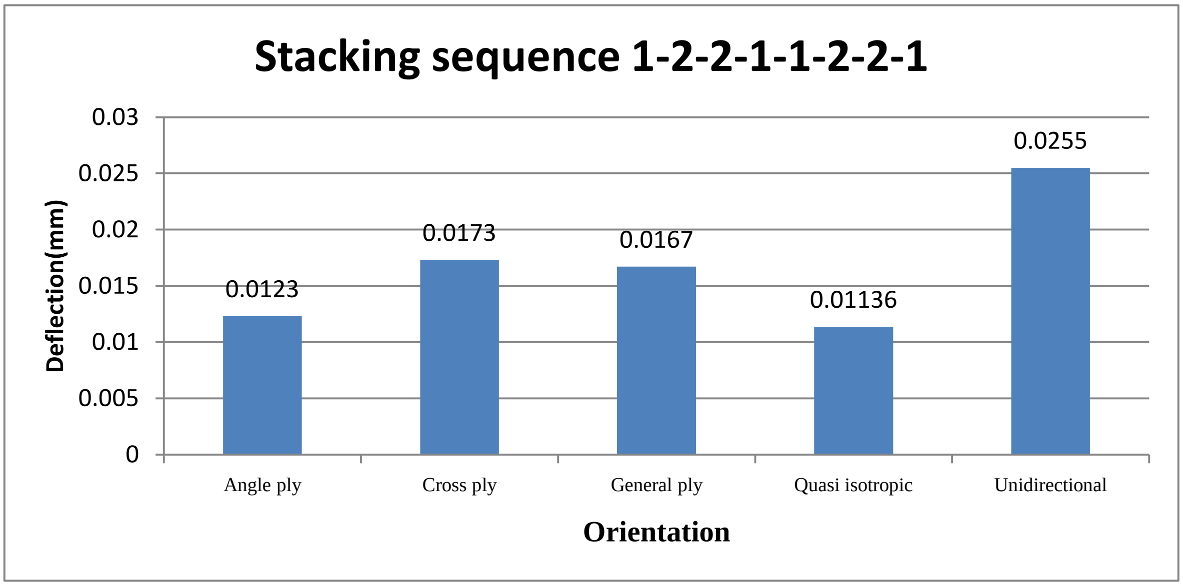


Figure 4.21 Deflection of plate under different ply angle

From above table 4.22 it can be observed that quasi-isotropic ply system shows minimum deflection. it means this angle system has maximum stiffness among all the ply angle system. But the failure index is minimum for angle ply system. So it has maximum failure stress.

4.5.2 Study of clamped –clamped configuration for 4 layers for similar way as doing above

Table 4.25 Stress distribution and deflection in stacking sequence 1-2-1-2

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.722	2.575	3.0812	0.07518	0.07510	0.0156
Cross ply	9.460	.4559	6.274	0.0577	0.0538	0.0257
General ply	6.5911	1.577	6.797	0.1631	0.1663	0.0232
Quasi isotropic	5.141	3.78	6.4581	0.0827	0.0966	0.03663
Unidirectional	7.328	2.0178	8.622	0.2471	0.2420	0.02637

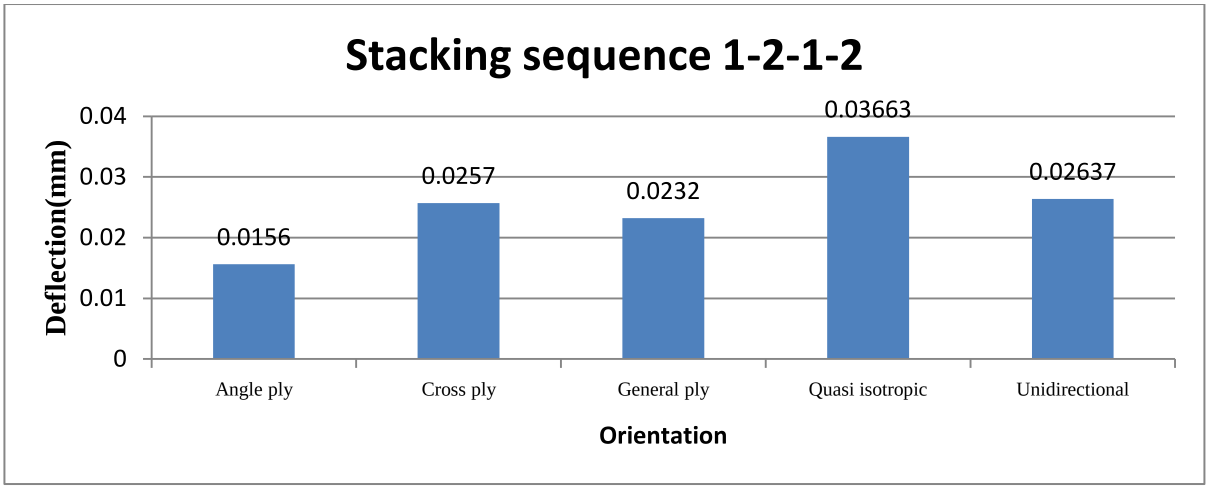


Figure 4.22 Deflection of plate under different ply angle

Table 4.26 Stress distribution and deflection in stacking sequence 2-2-1-1

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.648	2.542	3.092	0.0551	0.0432	0.0212
Cross ply	10.501	.6639	4.637	0.0587	0.0500	0.018
General ply	7.771	1.733	6.017	0.0789	0.0825	0.0171
Quasi isotropic	3.163	5.421	5.694	0.0475	0.0479	0.0429
Unidirectional	6.635	2.159	9.350	0.1249	0.1199	0.0287

Table 4.27 Stress distribution and deflection in stacking sequence 1-1-2-2

Orientation	Global Stress(MPa)			Failure index		Deflection(mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	4.648	2.542	3.092	0.0935	0.1024	0.0212
Cross ply	10.5016	.6639	4.637	0.1185	0.1146	0.018
General ply	7.771	1.733	6.0177	0.1795	0.1804	0.0171
Quasi isotropic	3.163	5.421	5.694	0.0865	0.1037	0.0429
Unidirectional	6.635	2.159	9.350	0.2167	0.2118	0.0287

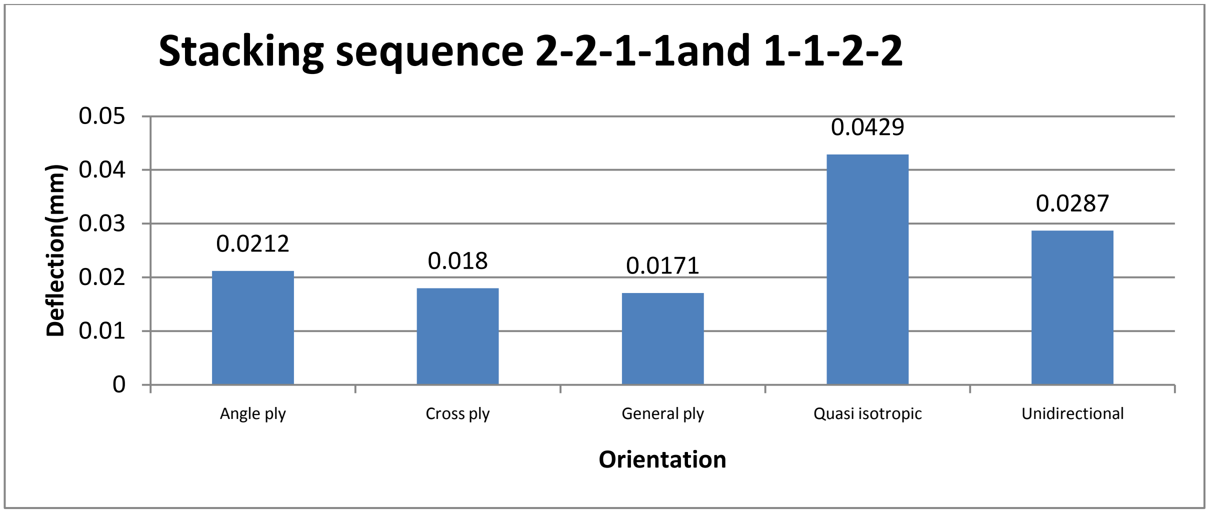


Figure 4.23 Deflection of plate under different ply angle

Table 4.28 Stress distribution and deflection in stacking sequence 1-2-2-1

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	3.661	2.295	2.392	0.0730	0.0571	0.0134
Cross ply	9.272	.6006	5.902	0.0747	0.0608	0.0194
General ply	7.617	1.354	6.071	0.0792	0.0788	0.0188
Quasi isotropic	6.121	6.169	8.012	0.0417	0.04641	0.04847
Unidirectional	8.104	1.146	7.924	0.1003	0.0924	0.02559

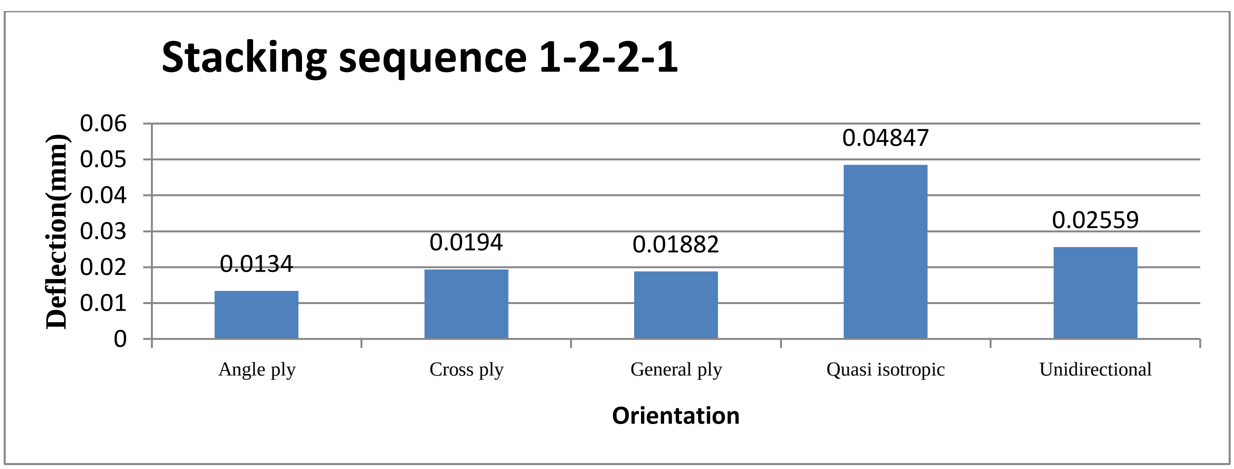


Figure 4.24 Deflection of plate under different ply angle

Table 4.29 Stress distribution and deflection in stacking sequence 2-1-1-2

Orientation	Global Stress(MPa)			Failure index		Deflection (mm)
	X	Y	XY	Maximum Stress	Tsai Wu	
Angle ply	2.679	1.628	1.426	0.0707	0.0804	0.0134
Cross ply	7.0639	.5004	3.709	0.0771	0.0730	0.0165
General ply	4.320	1.805	5.2518	0.1921	0.1933	0.0165
Quasi isotropic	3.443	3.974	4.381	0.0700	0.0868	0.0203
Unidirectional	3.4727	1.885	6.9997	0.2790	0.274	0.0255

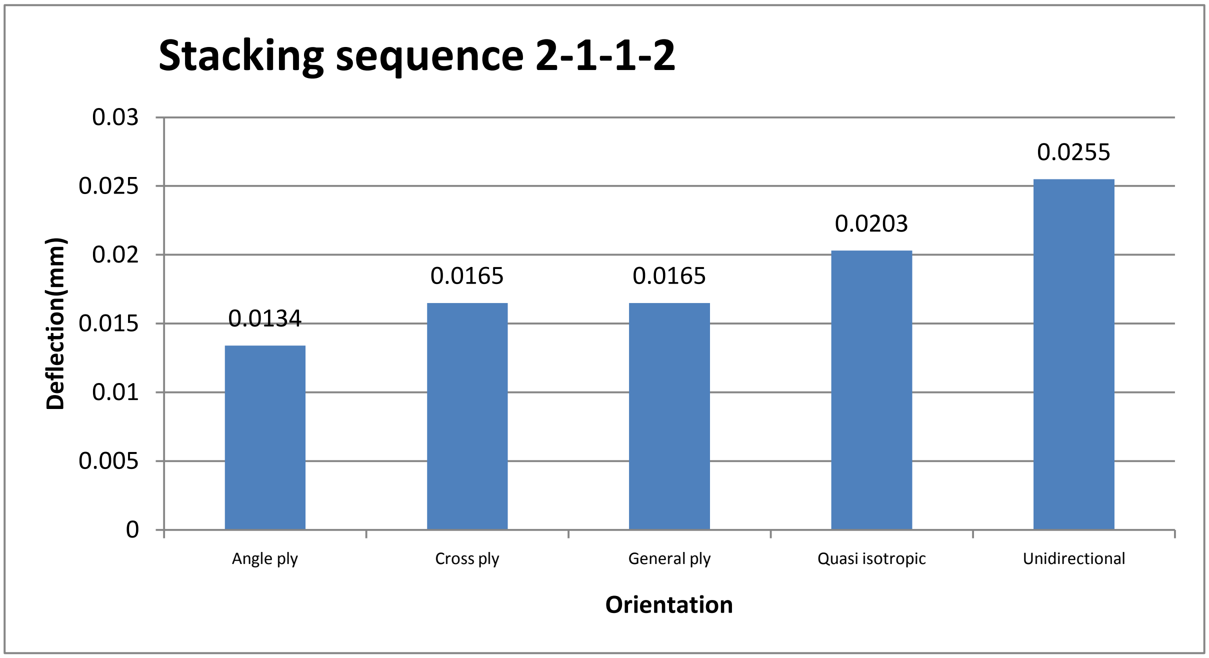


Figure 4.25 Deflection of plate under different ply angle

Now we decrease the number of lamina to four and the stacking sequence is vary same as vary previously. By comparing same stacking sequence with eight layer of lamina we found that the deflection in four layer stacking sequence system is more. So increasing number of layer is beneficial. But the failure index is increased in eight layer system. That means when we increased number of lamina then strength decrease but stiffness increases.

CHAPTER. 5 SUMMARY AND CONCLUSION

In the present work failure analysis of hybrid laminated composites has been performed. Parametric studies of hybrid lamina of different stacking sequence, ply orientation and number of lamina have been analyzed. We have taken two types of lamina one is graphite-epoxy and other is glass epoxy. Both the lamina are stacked different types of possible stacking sequence. The ply orientation is changed to study stiffness and failure index of hybrid laminated structure. In each iteration we have found global stresses in X direction, Y direction and shear stress in XY plane also failure theory index has been analyzed using Ansys software.

Following conclusions can be drawn from present investigation-

1. To validate finite element model of laminate first ply failure load of graphite-epoxy laminate is calculated using ANSYS and compared with experimental data **(Kam *et al.*)**. Tsai-Wu failure theory predicts better results than Maximum stress failure theory.
2. Failure index and deflection of laminates are calculated for different stacking sequence and different ply angle system of clamped-clamped and clamped-free configuration.
3. Among all the stacking sequence alternate stacking sequence shows maximum deflection hence this stacking sequence has minimum stiffness. Among alternating sequence unidirectional ply orientation shows maximum stiffness.
4. When stacking sequence reversed then deflection did not altered to corresponding angle system. But failure index changed.
5. Other than alternating stacking sequence general ply angle system shows minimum deflection. So general ply angle system shows maximum stiffness.
6. If we decreasing the number of layers of lamina then deflection is increases of corresponding stacking sequence, hence stiffness of laminate increases as number of lamina increases. Also failure strength increases with increase in number of lamina.
7. In alternating stacking sequence cross ply shows maximum strength among all the ply angle system
8. Results of Tsai-Wu failure theory and Maximum stress failure theory are very close.

9. The failure index and stiffness of different stacking sequence lamina and orientation of lamina varies same way for the both clamped-free and clamped-clamped configuration.