Critical Analysis of Filament Wound Glass Epoxy Composite Under Various Boundary Conditions

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ABSTRACT

Due to increasing demand and widespread application of Fibre reinforced polymer (FRPs) composites, they have been used in a variety of application like aerospace, automotive, sports, ships and constructional work. Because of their several advantages such as relatively low cost of production light weight, easy to fabricate and superior strength to weight ratio. In the present work Glass fibre is used as reinforcing agent. The objective of the present research work is to study the critical parameters that change the mechanical properties of Glass fibre reinforced epoxy based composites. The manufacturing method selected was filament winding, Critical parameters in present manufacturing method are winding angle & number of layers. These are the critical parameters used to study the mechanical properties of glass fibre reinforced epoxy based composites.

Keywords— Glass fibre, composites, Epoxy resin, Filament winding, layers, Laminate analysis

1. INTRODUCTION

1.1 Background and Motivation

A combination of two or more materials with different properties, or a system composed of two or more physically distinct phases separated by a distinct interface whose combination produces aggregate properties that are superior in many ways, to its individual constituents. A new material with combination of two or more material can provide enhanced properties that produce a synergetic effect [1].

In composite materials there are two constituents one is matrix and other is reinforcement. The constituents which is continuous and present in greater quantity is called matrix[1]. The main functions of the matrix is to holds or bind the fibre together, distribute the load evenly between the fibres, protect the fibre from mechanical and environmental damage and also carry interlaminar shear. While the other constituent is reinforcement; its primary objective is to enhance the mechanical properties e.g. stiffness, strength etc. The mechanical property depends upon the shape and dimensions of reinforcement . On the basis of type matrix
material, composites can be grouped into three main categories, polymer, metallic and ceramic. While on the basis of reinforcement classification of composite is shown in Figure 1.1 below:

![Figure 1.1 Classification of composite based on the type of reinforcement](image)

The main elements of polymer matrix composite are resin (matrix), reinforcement (e.g. fibre, particulate, whiskers), and the interface between them. The present work deals with the fibre reinforced polymer. FRP’s offers significant advantages, like combination of light weight and high strength to weight ratio and it is way easy to fabricate which is better than many metallic components.

The matrix of FRPs is further classified into-
I. Thermosetting resin
II. Thermoplastic resin

Thermoset resin (e.g. polyester, vinyl esters and epoxy) undergo chemical reaction that cross link the polymer chain and thus connect the entire matrix into three dimensional network due to this they possesses high dimensional stability, resistance to chemical solvent, and high temperature resistance. On the other hand unlike thermoset, curing process of thermoplastic resin (e.g. polyamide, polypropylene, and polyether-ether-ketone) is reversible. Their strength and stiffness depends on the molecular weight. They are generally inferior to thermoset in case of high temperature, strength, and chemical stability but are more resistant to cracking and impact damage.

As far we concerned about the reinforcement, there are wide variety of it, like natural fibre (e.g. hemp, kenaf, sisal, coir, jute etc), synthetic fibre (e.g. glass fibres, ceramic etc) and organic fibre (e.g. aramid)[1]. Natural fibres are cheap, easily available, and bio-degradable but these advantages are not sufficient to overcome their major drawbacks like moisture absorption, It can be easily attacked by chemicals and has low strength compared to synthetic fibres. Now, in manmade fibres there are two types of fibres,
1. Synthetic fibre
2. Organic fibre

There are numerous types of synthetic fibres such as nylon, acrylic, polyester, glass fibres etc. Now a day most commonly used synthetic fibre is glass fibres. There are also varieties of glass fibres e.g. A-glass, C-glass, D-glass, E-CR glass, E- glass and S-glass, among them E-glass and S-glass are most widely and commonly used, in many industry they represent over 90% of reinforcements used[1].
Glass fibres which are available commercially are mainly manufactured in the form of woven roving (cloth), chopped strands, long continuous fibres. Woven roving’s consist of continuous roving, which is a fabric woven in two mutually perpendicular directions. In chopped strand, continuous fibres are cut to the short length and fibres are arranged in the form of bundle. On the other side S-glass has higher tensile strength, greater modulus and higher elongation at failure compared to the E-glass, and S-glass is mainly used where strength is a primary concern along with weight e.g. airplane fuselage, tail wings of airplane, pipes for carrying aqueous liquid, ship hulls, helicopter blades, tanks and vessels. But its cost is a primary issue which restrict its application in commonly used items like household appliances e.g. fibre glass doors, window frame, bath tub etc. and sports items e.g. hockey sticks, fishing rod, arrow of archery etc.. The different types of glass fibres are listed in the Table 1.1 below.

In E-glass fibre the term “E” stands for electric, which is made from alumino-borosilicate glass containing oxides of alkali less than 1% by weight, C-glass has high content of boron oxide, whereas S-glass having high content of magnesium oxide with silica and aluminium oxide. The typical composition of different glass fibres are shown in the Table 1.2 given below.

### Table 1.2 Composition and properties of glass fibres [1]

<table>
<thead>
<tr>
<th>Composition s (%)</th>
<th>E-glass</th>
<th>S-glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>52.4</td>
<td>64.4</td>
</tr>
<tr>
<td>Al2O3 + Fe2O3</td>
<td>14.4</td>
<td>25.0</td>
</tr>
<tr>
<td>CaO</td>
<td>17.2</td>
<td>-</td>
</tr>
<tr>
<td>MgO</td>
<td>4.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Na2O + K2O</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>B2O3</td>
<td>10.6</td>
<td>-</td>
</tr>
<tr>
<td>BaO</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Organic fibre- The commonly used organic fibre derived from aromatic polyamides possesses high modulus, are called aramid fibres. They were first developed by Du Pont with the trade name “Kevlar”. They derived from the polymer molecules those have high degree of aromaticity (containing benzene rings in their structure) which possesses crystalline behaviour in liquid solution. They are usually produced from spinning and extrusion process [1]. Its common application are in rail carriage, for temperature resistance environment like hoses, tyres, brake pads and belts, ballistic helmets in military applications. Due to its property like high tensile strength, light weight and dielectric property it is also used in wide variety of optical fibre applications.

In the present work randomly oriented short E-glass fibre is used as reinforcing agent because of its good strength, light weight, chemical resistance and more importantly its low cost. Aluminium oxide (Al2O3) also called as alumina is used as a filler material. The addition of filler to the composites enhances the mechanical as well as physical properties . The properties of Al2O3 like chemical inertness, high hardness,
good strength and less expensive made it fit for the use where friction and wear conditions are predominant e.g. for low cost automotive brake linings. Pure aluminium is chosen as coating material because of its wear and corrosion resistance property due to its passivation effect (it is the property of material to form thin coating film of its oxide and prevents its surface from foreign factors e.g. air and moisture). And also filler material is compound of aluminium.

1.2 Advantages of FRP:
FRP composites consist of an engineered polymer (plastic) and a reinforcement (i.e. glass) and can be additionally enhanced with other elements such as additives and core materials. This combination can produce some of the strongest materials for their weight that technology has ever developed...and the most versatile.

FRP composites have many benefits to their selection and use. The selection of the materials depends on the performance and intended use of the product. The composites designer can tailor the performance of the end product with proper selection of materials. It is important for the end-user to understand the application environment, load performance and durability requirements of the product and convey this information to the composites industry professional. FRP composites provide a host of benefits ideal for structural applications including.

**High Strength and Stiffness Retention:**
Composites can be designed to provide a wide range of mechanical properties including tensile, flexural, impact and compressive strengths. And, unlike traditional materials, composites can have their strengths oriented to meet specific design requirements of an application.

**Light Weight/Parts Consolidation:**
FRP composites deliver more strength per unit of weight than most metals. In fact, FRP composites are generally 1/5th the weight of steel. The composite can also be shaped into one complex part, often times replacing assemblies of several parts and fasteners. The combination of these two benefits makes FRP composites a powerful material system- structures can be partially or completely pre-fabricated at the manufacturer's facility, delivered on-site and installed in hours.

**Creep (Permanent Deflection Under Long Term Loading)**
The addition of the reinforcement to the polymer matrix increases the creep resistance of the properly designed FRP part.

**Resistance to Environmental Factors:**
Composites display excellent resistance to the corrosive effects of:

**Freeze-thaw:** because composites are not attacked by galvanic corrosion and have low water absorption, they resist the destructive expansion of freezing water.

**Weathering and Ultra-Violet Light:**
FRP composite structures designed for weather exposure are normally fabricated with a surface layer
containing a pigmented gel coat or have an ultraviolet (UV) inhibitor included as an additive to the composite matrix. Both methods provide protection to the underlying material by screening out UV rays and minimizing water absorption along the fiber/resin interface.

2. MATERIALS AND METHODS
This section deals with different material and processing technique used for the fabrication of composite under this present work. It provides the details of tests and characterization which are conducted on composite samples.

2.1 Materials

2.1.1 Matrix
Polymer matrices are most common and widely used matrix material, because of its availability, easiness to fabrication, light weight and low cost compared to others. The matrix material used in the present work is epoxy resin which belongs to the class of thermoset material that contains epoxide group as its functional element in which one oxygen atom is bonded to two carbon atoms.

![Figure 2.1 The epoxide group](image)

Among all thermoset resin, epoxy resin is widely used as matrix material. It forms three dimensional cross-link structures after undergoing irreversible chemical reaction. It possesses several benefits over other thermoset resin like superior mechanical strength, good bonding with various type of fibres, low shrinkage upon curing and resistant to chemicals. Because of several advantages over other types of resin, epoxy resin LY-556 is picked as matrix material. Commonly used epoxy is Diglycidyl Ether of Bisphenol-A. The chemical structure of epoxy is shown below.

![Figure 2.2 Chemical structure of diglycidyl ether of bisphenol-A](image)

2.1.2 Fibre material
Glass fibres are most common reinforcing agent among various composite materials. Glass fibres are available in the form of woven fabric, chopped strands, long continuous fibre and short discontinuous fibre. In present research work randomly oriented continuous E-glass fibre is used as reinforcing agent. It is basically an ordinary borosilicate glass containing less than 1% of alkali oxides.
3. COMPOSITE FABRICATION

3.1 Silane Coupling Agent:
Silane coupling agents have the ability to form a durable bond between organic and inorganic materials. Encounters between dissimilar materials often involve at least one member that’s siliceous or has surface chemistry with siliceous properties; silicates, aluminates, borates, etc., are the principal components of the earth’s crust. Interfaces involving such materials have become a dynamic area of chemistry in which surfaces have been modified in order to generate desired heterogeneous environments or to incorporate the bulk properties of different phases into a uniform composite structure.

![Figure 3.1 General formula for a silane coupling agent](image)

The general formula for a silane coupling agent typically shows the two classes of functionality. X is a hydrolyzable group typically alkoxy, acyloxy, halogen or amine. Following hydrolysis, a reactive silanol group is formed, which can condense with other silanol groups, for example, those on the surface of siliceous fillers, to form siloxane linkages.

Stable condensation products are also formed with other oxides such as those of alu-minum, zirconium, tin, titanium, and nickel. Less stable bonds are formed with oxides of boron, iron, and carbon. Alkali metal oxides and carbonates do not form stable bonds with Si-O-. The R group is a nonhydrolyzable organic radical that may posses a functionality that imparts desired characteristics.

The final result of reacting an organosilane with a substrate ranges from altering the wetting or adhesion characteristics of the substrate, utilizing the substrate to catalyze chemical transformations at the...
heterogeneous interface, ordering the interfacial region, and modifying its partition characteristics. Significantly, it includes the ability to effect a covalent bond between organic and inorganic materials. Most of the widely used organosilanes have one organic sub-stituent and three hydrolyzable substituents. In the vast majority of surface treatment applications, the alkoxy groups of the tri-alkoxysilanes are hydrolyzed to form silanol-containing species. Reaction of these silanes involves four steps. Initially, hydrolysis of the three labile groups occurs. Condensation to oligomers follows. The oligomers then hydrogen bond with OH groups of the substrate. Finally during drying or curing, a covalent linkage is formed with the substrate with concomitant loss of water. Although described sequentially, these reactions can occur simultaneously after the initial hydrolysis step.

At the interface, there is usually only one bond from each silicon of the organosilane to the substrate surface. The two remaining silanol groups are present either in condensed or free form. The R group remains available for covalent reaction or physi-cal interaction with other phases.

Silanes can modify surfaces under anhydrous conditions consistent with monolayer and vapor phase deposition require-ments. Extended reaction times (4-12 hours) at elevated tem-peratures (50°-120°C) are typical. Of the alkoxysilanes, only methoxysilanes are effective without catalysis. The most effec-tive silanes for vapor phase deposition are cyclic azasilanes

Water for hydrolysis may come from several sources. It may be added, it may be present on the substrate surface, or it may come from the atmosphere.

The degree of polymerization of the silanes is determined by the amount of water available and the organic substituent. If the silane is added to water and has low solubility, a high degree of polymerization is favored. Multiple organic substitution, particularly if phenyl or tertiary butyl groups are involved, favors formation of stable monomeric silanols.

The thickness of a polysiloxane layer is also determined by the concentration of the siloxane solution. Although a monolayer is generally desired, multilayer adsorption results from solutions customarily used. It has been calculated that deposition from a 0.25% silane solution onto glass could result in three to eight molecular layers. These multilayers could be either inter-connected through a loose network structure, or intermixed,or both, and are, in fact, formed by most deposition techniques. The orientation of functional groups is generally horizontal, but not necessarily planar, on the surface of the substrate.

The formation of covalent bonds to the surface proceeds with a certain amount of reversibility. As water is removed generally by heating to 120°C for 30 to 90 minutes or evacuation for 2 to 6 hours, bonds may form, break, and reform to relieve internal stress. The same mechanism can permit a positional displacement of interface components.

3.2 Composite Fabrication :-

Finished products are formed from materials such as plastics and metals by molding or shaping methods. The material is first created and then processed at a later stage by companies specializing forming, sheet
forming, injection molding, etc. However, products consisting of composites can be created simultaneous with the creation of the material. Such is the case when filament winging a pipe from a polymer and glass fiber strands.

With regards to polymeric matrix composites, the processing methods for thermosetting materials typically involve material formation during final molding (e.g., hand lay-up, and vaccum-bag molding). In some cases material formation is accomplished separately from forming or shaping, but because of the curing nature of thermosetting resins, final curing occurs during final formation. In thermoplastic matrix composite properties still can be influenced (e.g., fiber length reduction or fibre orientation during molding).

The choice of a fabrication process is strongly influenced by the chemical nature of the matrix (e.g., thermoset or thermoplastic in case of a polymer) and te temperature required to form, melt, or cure the matrix.

3.2.1 Filament Winding:

Filament winding is a fabrication technique mainly used for manufacturing open (cylinders) or closed end structures (pressure vessels or tanks). The process involves winding filaments under tension over a male mandrel. The mandrel rotates while a wind eye on a carriage moves horizontally, laying down fibers in the desired pattern. The most common filaments are carbon or glass fiber and are coated with synthetic resin as they are wound. Once the mandrel is completely covered to the desired thickness, the resin is cured, often the mandrel is placed in an oven to achieve this, though sometimes radiant heaters are used with the mandrel still turning in the machine. Once the resin has cured, the mandrel is removed, leaving the hollow final product. For some products such as gas bottles the 'mandrel' is a permanent part of the finished product forming a liner to prevent gas leakage or as a barrier to protect the composite from the fluid to be stored.

Filament winding is well suited to automation, and there are many applications, such as pipe and small pressure vessel that are wound and cured without any human intervention. The controlled variables for winding are fiber type, resin content, wind angle, tow or bandwidth and thickness of the fiber bundle. The angle at which the fiber has an effect on the properties of the final product. A high angle "hoop" will provide circumferential or "burst" strength, while lower angle patterns (polar or helical) will provide greater longitudinal tensile strength.
The simplest winding machines have two axes of motion, the mandrel rotation and the carriage travel (usually horizontal). Two axis machines are best suited to the manufacture of pipes only. For pressure vessels such as LPG or CNG containers (for example) it is normal to have a four axis winding machine. A four-axis machine additionally has a radial (cross-feed) axis perpendicular to carriage travel and a rotating fibre payout head mounted to the cross-feed axis. The payout head rotation can be used to stop the fibre band twisting and thus varying in width during winding.

Machines with more than four axes can be used for advanced applications, six-axis winding machines usually have 3 linear and 3 rotation axes. Machines with more than 2 axes of motion have computer/CNC control, however these days new 2-axis machines mostly have numeric control. Computer controlled filament winding machines require the use of software to generate the winding patterns and machine paths, such software can normally be provided by filament winding machine manufacturers or by using independent products such as Cadfil or Cadwind, a review of programming techniques for CNC machines can be found in. An example of such a winding process can be found all throughout the web. also continuous winding systems are available these days.

Filament winding can also be described as the manufacture of parts with high fiber volume fractions and controlled fiber orientation. Fiber tows are immersed in a resin bath where they are coated with low or medium molecular weight reactants. The impregnated tows are then literally wound around a mandrel (mold core) in a controlled pattern to form the shape of the part. After winding, the resin is then cured, typically using heat. The mold core may be removed or may be left as an integral component of the part(Rosato, D.V.).This process is primarily used for hollow, generally circular or oval sectioned components, such as pipes and tanks. Pressure vessels, pipes and drive shafts have all been manufactured using filament winding. It has been combined with other fiber application methods such as hand layup, pultrusion, and braiding. Compaction is through fiber tension and resin content is primarily metered. The fibers may be impregnated with resin before winding (wet winding), pre-impregnated (dry winding) or post-impregnated. Wet winding has the advantages of using the lowest cost materials with long storage life and low viscosity. The pre-impregnated systems produce parts with more consistent resin content and can often be wound faster.

Glass fibre is the fibre most frequently used for filament winding, carbon and aramid fibres are also used. Most high strength critical aerospace structures are produced with epoxy resins, with either epoxy or cheaper polyester resins being specified for most other applications. The ability to use continuous reinforcement without any breaks or joins is a definite advantage, as is the high fibre volume fraction that is obtainable, about 60% to 80% only the inner surface of a filament wound structure will be smooth unless a secondary operation is performed on the outer surface. The component is normally cured at high temperature before removing the mandrel. Finishing operations such as machining or grinding are not normally necessary.

Filament winding is a type of composite manufacturing process, where controlled amount of resin and oriented fibers are wound around a rotating mandrel and cured to produce the required composite part. It
was initially used to produce pressure vessels, water and chemical tanks. The development stage of filament winding goes back to dry wire winding of rocket motor cases, which requires reinforcement. Today, the applications include aircraft fuselages, wing sections, radomes, helicopter rotor shafts, high-pressure pipelines, sports goods and structural applications of all types.

Most filament winding machines look like a lathe. The mandrel is supported horizontally between a head and tail stoke. The tail stoke is free, but head stoke is driven by required angle and speed, using a computer program. As the mandrel rotates, a carriage travels along the mandrel and delivers fiber with a given position and tension. Carriage motion is also controlled by the computer; in connection with head stoke rotation.

Winding machines are characterized by their degrees of freedom. Two of these degrees of freedoms are already defined: rotation of head stoke and horizontal movement of the carriage. Other commonly used degrees of freedoms are vertical and rotational motion of the delivery eye.

Fibers pass through a resin bath after tensioning system and gets wet before winding operation. When a pre-impregnated fiber or prepreg is used, wetting is not performed.

Tensioning system is an important part of filament winding. This importance gets critical when winding at high angles. Since tension changes the friction force between fiber and the mandrel, it should be kept at a certain value during winding operation. Fiber tension also affects the volumetric ratio of composite at a given point. Excessive resin, due to a low tension, can result in decreased mechanical properties. Therefore, tensioning systems should be capable of rewinding a certain value of fiber. This condition occurs when fiber band reverses at the end of tube, while winding at low angles.

Figure 3.3 Schematic View of a Filament Winding Machine

Wetting can be done by two commonly used bathing type; drum bath and dip bath. Drum bath provide less fiber damage than dip bath. This is especially important when using carbon fibers. On the other hand, dip bath provides a better wetting action. If fibers are not wetted in a desired way, air bubbles can be
trapped between them and can cause voids in the composite part. Therefore, drum baths can be heated for a better wetting action.

Lowering resin viscosity, reducing fiber speed, increasing fiber path on the drum are other methods used for better wetting action. Dip baths are used with aramid or glass fibers. If heated resin is to be used, dip baths are preferred since drum surface cools as it leaves the resin bath. During the travel of fiber through a dip bath, non-rotating surfaces are used for guidance. Non-rotating surfaces provide good wetting, and prevents fiber built out due to broken fibers at rotating surfaces.

**Figure 3.4 Schematic View of a Drum Bath**

Delivery eyes can be in a variety of different shapes. The shapes are defined according to the type of application and type of fiber. Like all other fiber-connecting parts, wear should be evaluated by use of hard aluminum parts and chrome coated steel parts.

Rotating mandrel can be a part of the produced composite part (such as in production of a pressure vessel with a liner) or can be removed from composite part (such as a composite tube). If it will be removed, a press should be used for removing. All mandrels, which will be removed, should have low thermal expansions in order to reduce residual stresses after curing action. Steel is generally used when producing mandrels. If a tube is used as a mandrel, tube thickness should be uniform, in order to have a symmetric composite part. In addition, surface finish is an important point, since an interface between the composite part and mandrel is generally not permitted.

**Figure 3.5 Schematic View of a Dip Bath**
If a concave part is needed on the filament wound part, a female mold can be used. In addition, excessive wet fiber can be used in order to fill concave parts. Metal parts can be mounted on mandrel in order to guide winding action.

Winding angle is the angle between fiber and the line on surface of the mandrel, which is parallel to mandrel axis. A maximum value, which is close to 90 degrees, can be approximated. Very low winding angle values need some arrangements at the ends of the mandrel, such as pins, etc. There are many reasons to use filament winding as a composite manufacturing method. First, many part such as rocket motor cases or pressure vessels require reduced radius at the end openings. For these applications, generally a metal, plastic or rubber liner is used. Rubber liners require a dissolvable material in order to support the rubber liner

![Fiber Orientation Angle](image)

**Figure 3.6 Fiber Orientation Angle**

Secondly, filament winding is an effective way to produce high strength tubes. This situation holds especially when there exists an internal pressure. In addition, it is even possible to wound endless tubes for pipelines, etc. Having no connection points, endless tubes are more economical and reliable. Winding angles can also be arranged in order to optimize the design for several usage purposes.

It is possible to use filament winding for reinforcement. Thick pressure vessels, rocket motor cases are all examples of this kind of applications. As mentioned before, filament winding can even be used to reinforce concrete columns.

When designing and producing a filament wound tube, one has to consider many possibilities and limitations. The first limitation will be the winding machine used. For complex geometries, machines that are more complex should be employed. The dimensions of the machine, the number of degrees of freedom, control unit used and the pattern generation software directly affect the limits of winding action. A three or four axis computer controlled filament winding machine will be practical for most cases.

Today, use of high-tech robotic winding machines even makes it possible to wind T joints of pipes.

Second limitation will be the mandrel geometry that is used. Concave geometries are generally not permitted. Sharp edges should be avoided in order not to cut fibers. End edges should not restrict returns
of winding. Pins or domes must be removable or collapsible. Surface finish of the mandrel should meet the requirements.

Difficulty of winding action is a limitation on filament winding. Fibers can be wound on the mandrel along different trajectories. Geodesic or semi-geodesic curves can be used in order to wind geometry. Similar to works done on textile industry, there are many applications on these geodesic pads and filament winding process. Deviation of fiber from these geodesic pads increases the slippage and textile point of view gets more importance. Ends of tube are the main critical point for these geodesic pads.

When the tube is subjected to a loading condition, all layers of fibers should be stressed equally. This simply implies that, for each loading condition there exists an optimum winding configuration. This makes the research and testing action necessary for filament winding applications. These are difficult design items due to the complexity of composite material behavior. Some assumptions can be done in order to simplify an analysis. If woven structure is neglected, there exist three mutually perpendicular planes in each lamina. Elastic properties are symmetric about these planes. These planes are the cross-section, the fiber plane and a plane passes through axis of the cylinder. Using this configuration, usually all design work on filament winding is performed.

3.3 Mechanical testing of composites

The tensile test is conducted on all the samples as per ASTM D3039-76 test standards. Specimens are positioned in the grips of universal testing machine and a uniaxial load is applied through both the ends until it gets failure. During the test, the crosshead speed is taken as 2 mm/min as per ASTM standards, specimens of rectangular cross-sections having length and width of 100 mm and 15 mm respectively are used.

3.4 Analysis of a Laminated Composite :-

Strain-Field in a Laminate

Assumptions for variation of strains in a laminate these are:

Laminates are manufactured so that they act as single-layer materials. In typical applications, such a response from the laminate is required so that its overall strength and stiffness can be maximized.

The requirement of “single-layer materials” necessitates that the adhesive bond between two adjacent layers is perfect in the sense it has:

Almost zero thickness

No shear deformation - Thus, adjacent lamina cannot slip over each other.

The assumption of “single-layer material” also implies that displacements are continuous across the bond between two adjacent layers. Laminates are thin in the sense their overall thickness is significantly smaller other dimensions of the laminate.

Strain-Field in a Laminate

Consider Fig.3.6. The figure shows how a section of laminate, taken in x-z direction, appears after deformation due to application of forces. Here, z, is the thickness direction on reference coordinate system.
Strain-Field in a Laminate:

The lower left-side portion of Fig. is a view of un-deformed laminate. The lower right-side portion of Fig. shows the deformed state of laminate’s section.

In the un-deformed section, line ABCD, is perfectly straight and normal to mid-plane of the laminate. This line is assumed to remain straight and normal to mid-plane even after getting deformed. This implies that:

Out-of-plane shear strains $\gamma_{xz}$ and $\gamma_{yz}$ are zero.

There is no inter-laminar shear or slipping.

Further, it is assumed that the length of line ABCD remains same after deformation. This in turn implies that strain in $z$ direction, $\varepsilon_{zz}$, is zero.

Assumptions of normality, in-extensibility and straightness for line ABCD are together known as Kirchhoff-Love assumptions in shell theory, and Kirchhoff’s assumptions in plate theory.

Further, due to deformation of plate, point B undergoes translation by amount $u^o$, $v^o$, and $w^o$, in $x$, $y$, and $z$ directions, respectively. Also, the line ABCD rotates about B by an angle $\alpha$ in the $z$ plane. Figure 25.1 does not show $v_o$ displacement explicitly because the figure is a side view of the laminate undergoing deformation.

Thus, displacement of point C, which is $z$ distance away from mid-plane is:

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**Figure 3.7**: Deformation of laminate as viewed in X-Y plane

**Figure 3.8**: Stacking of piles into composite laminate with different orientation
\[ u = u_0 z \alpha \]

Where \( \alpha \) is the slope of laminate midplane in the \( x \) direction, that is

\[ \alpha = \frac{\partial W_0}{\partial X} \]

from above two equations, an expression for displacement \( u \) in the \( x \) direction of an arbitrary point at a distance \( z \) from the midplane is obtained:

\[ u = u_0 z \frac{\partial W_0}{\partial X} \]

The displacement \( w \) in the \( z \) direction of any point on ABCD is the displacement \( w_0 \) of the midplane plus the stretching of the normal. It is assumed that the stretching (or shortening) of the normal (ABCD) is insignificant \( w_0 \), and thus the normal displacement of any point in laminate is taken to be equal to be equal displacement \( w_0 \) of the corresponding point at the midplane. Thus the normal strains \( \varepsilon_z \) are neglected. This reduces the laminate strains to \( \varepsilon_x \), \( \varepsilon_y \), and \( \tau_{xy} \). These strains can be obtained for the derived displacement \( u \) and \( v \) as follows:

\[
\begin{align*}
\varepsilon_x &= \frac{\partial U}{\partial X} = \left( \frac{\partial U_0}{\partial X} \right) - z \left( \frac{\partial^2 W_0}{\partial X^2} \right) \\
\varepsilon_y &= \frac{\partial U}{\partial Y} = \left( \frac{\partial V_0}{\partial Y} \right) - z \left( \frac{\partial^2 W_0}{\partial Y^2} \right), \\
\tau_{xy} &= \left( \frac{\partial U_0}{\partial Y} \right) + \left( \frac{\partial V_0}{\partial X} \right) - 2 z \left( \frac{\partial^2 W_0}{\partial X \partial Y} \right)
\end{align*}
\]

**Stresses in a Laminate**

If one were able to compute mid-plane strains and curvature of the plate, then predicting stresses over the laminate’s thickness is simply a matter of multiplying these strains with stiffness constants using strain-stiffness relations on a layer-by-layer basis.

Thus, stresses in \( k^{th} \) layer of the laminate may be calculated using following relations.

\[
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\tau_{xy}
\end{bmatrix} = \begin{bmatrix}
Q_{11} & Q_{12} & Q_{16} \\
Q_{12} & Q_{22} & Q_{26} \\
Q_{16} & Q_{26} & Q_{66}
\end{bmatrix} \begin{bmatrix}
\varepsilon_{xx}^0 \\
\varepsilon_{yy}^0 \\
\gamma_{xy}^0
\end{bmatrix} + z \begin{bmatrix}
k_x \\
k_y \\
k_{xy}
\end{bmatrix}
\]

Since \( [Q] \) matrix varies discontinuously between two adjacent layers, variation of stresses between two layers need not be linear, or even continuous. Thus stresses are discontinuous between two adjacent layers, even though strain varies linearly across entire laminate thickness. However, over the thickness of a single lamina, stress variation is linearly continuous.

**3.5 Comparison of Composite Materials And Metals**

Regarding the design stage, composites and traditional metals are somewhat different. Designing structural components, using metals are usually straightforward. The geometry of the structural element is designated first, and then the material and production method is defined at the final stage. However, composites require the material to be designed along with the structure. Therefore, optimization of the
design and iterations are usually required in the first steps of composite design. The verification of the complete design, which is done by testing, is also very important in composite structures. Considering geometrical form, composites can give large design flexibility for the designers. Having a large number of manufacturing alternatives, almost all geometries can be produced with a low cost production and tooling. Fasteners or parts can be removed with a unique composite part production. This minimizes the cost and increases weight efficiency of designed structures. Electrical properties also make composites functional for designers. They can also be used for conductor parts when they are produced with some filler types. Composites have lower specific gravity when compared to traditional material (Fig. 3.9).

Most of the composite materials have higher specific modulus of elasticity when compared to traditional metallic materials. This is due to low specific gravity of composite materials. A comparison of modulus of elasticity and specific modulus of elasticity of various materials can be seen in Fig. 3.10 and 3.11.

![Figure 3.9 - Specific Gravity of various materials](image)

![Figure 3.10 - Modulus of Elasticity of various materials (GPa) [4](image)

Both strength and specific tensile strength properties of composites are higher than most of the traditional metallic materials. Comparison of tensile strength and specific tensile strength of various materials can be seen in Fig.

![Figure 3.11 - Specific Modulus of Elasticity of various materials (10^9 m) [4](image)
Composites also have a higher fatigue resistance. Therefore, aerospace and automotive industry commonly employs high performance composite parts. Another important characteristic of composites is their low coefficient of thermal expansion.

Composites are also resistant to rusting or corroding. So, they are widely used in military, marine or water system applications. Acid resistance is another point, which makes composites superior to metals. There are some chemicals, which effect molecular structure of polymer based composite materials.

Nevertheless, surface coating can be solution to this problem. Surface finishes of composites are also good. Although quality of a surface depends on manufacturing method, composites generally do not require a surface treatment. They can be directly painted with most of the metallic or non-metallic paints.

All above-mentioned characteristics make composite an essential source for structural engineering design. The increasing practice of composites in all brands of industries gives rise to development of new concepts in composite structures. These ascend will further increase the fraction of composite materials in engineering structures.

4. RESULTS AND DISCUSSION

Composite Modeling With Ansys
Modeling composites within any FEA software has three important stages different than modeling any isotropic material: choosing proper element type, defining the layers of the element and defining the failure criteria for the material.

ANSYS has more than 40 different material models, such as linear elastic models, nonlinear elastic models, nonlinear inelastic models, foam models, pressure dependent plasticity models or equation of state models, etc. Within these models, composite materials can be modeled using layered elements with orthotropic or anisotropic material properties.

In order to model layered composite materials, ANSYS serves a number of layered element types:
SHELL 99- Linear Layered Structural Shell Element,
SHELL 91 - Nonlinear Layered Structural Shell Element,
SHELL 181 - Finite Strain Shell,
SOLID 46- 3-D Layered Structural Solid Element,
SOLID 191- Layered Structural Solid Element,

In addition, SOLID 95, SHELL 63 and SOLID 65 elements can also be used for composite modeling with some key options; basically for single layers or for approximate calculations. The type of element to be used in the model depends on the specific application, and the results that are needed at the end of the analysis. As a rule in finite element analysis technique: if one dimension of the model is 10 or more times greater than the other two, shell elements should be preferred instead of solid elements. If two dimension of the model is 10 or more times greater than the other one, beam elements should be preferred [36].

Shell elements can be imagined as collapsed solid elements, which have negligible through thickness stress values. Since some edges are absent in shell elements, generally more degrees of freedom (rotational degrees of freedom) are defined for nodes of a shell element.

For our specific application, solid elements should not be used due to geometrical considerations. SHELL 91 is not preferred either, since it is used with nonlinear applications such as large strain, sandwich construction or plasticity. SHELL 181 is not preferred since highly nonlinear behavior exists.

Layered configuration can be modeled by specifying the layer properties; such as material properties, orientation angle, layer thickness and number of integration points per layer. For SOLID 46 and SHELL 99 element types of ANSYS, constitutive matrices can be defined with an ‘infinite number of layers’ opportunity. Within layered configuration, SHELL 63, SHELL 91, SHELL 181 and SHELL 63 elements of ANSYS permit sandwich construction using one layer and real constants. It is possible to model ply drop-off, by using SHELL 181, SHELL 91 and SHELL 99 elements, by the method of node offsetting.

ANSYS permits to use three different failure criterions for composites: Maximum Strain Failure Criterion, Maximum Stress Failure Criterion and Tsai-Wu Failure Criterion. Within these models, failure strains, failure stresses and coupling coefficients in all directions of orthotropy or anisotropy can be modeled as a temperature dependent parameter.

ANSYS Parametric Design Language can be used in analyzing a composite structure. See ‘Section 4.2’ for details on APDL.

For an application, it should be decided whether which element type or material model to use. Then the layered configuration should be defined. Layer orientation and orthotropic properties should be checked. Before running the analysis, failure criteria should be chosen.

**Ansys Parametric Design Language**

ANSYS Parametric Design Language (APDL) is a script language that can be used for developing macro files, which are capable of self-executing an analysis. They can contain if-then-else branching, do-loops, subroutines, and matrix operations, repeating, reading and storing data. Macro files can be used
to automate common operations such as building geometry or analyzing it. More than one macro files can be called within an analysis. APDL can perform repeating analyses, with changing variables. APDL is such open ended that; it can even be used to optimize a structure using only one or more well-written macro file. APDL permits some operations, which cannot be performed by graphical user interface of ANSYS, such as fatigue analyses [36].

APDL is an important tool for composite analyses, since it can repeat any analysis within a very short time. This tool can be used for analyzing composites, such as determining maximum value of Tsai-Wu failure index for a complicated composite part. APDL is mainly important in optimization of a composite structure; such as layer orientations of a filament wound tube under specified loading conditions.

They are capable of analyzing internal pressure loading of layered orthotropic tubes and combined loading of layered orthotropic tubes, respectively. The user is allowed to give input data of dimensions of tube, number of layers and their orientation, elastic properties, strength properties, mesh intensity and boundary conditions and loading. Post-processing of the analysis is not performed within these macro files. Looping for optimization is not performed.

**Ansyl APDL Modeling of Homogeneous Layered Orthotropic Tubes Under Combined Loading**

Within the scope of the thesis, two APDL script is written in order to analyze filament wound composite tubes, under combined loading and internal pressure loading, respectively.

In the FEA model of the filament wound tubes, the tubes are assumed to be made of orthotropic adjacent layers. Therefore, crossing of fibers and changes in the fiber orientation are neglected. All layers are assumed equal in thickness and the thicknesses of the layers are calculated by dividing the thickness of the tube by the number of layers.

In ‘Internal Pressure Loading Analysis’, the tube is fixed from a node at one end and internal pressure is applied to inner surface of the tube (Fig. 4.1). There are no other constraint or loading in this analysis.

![Figure 4.1 Loading and Constraints of Internal Pressure Loading](image)

In ‘Combined Loading Analysis’, the tube is fixed from one end, by applying ‘all DOF constraint’ on end lines of the tube surface. Then, an axial load, a transverse load and a torque are applied to the other
end, namely on nodes within the fixing length. This fixing length is specified during entering user-defined inputs. Tube dimensions can be found in Table 4.1.

![Figure 4.2: Loading and Constraints of Combined Loading](image)

**Table 4.1 – Dimensions of The Tube**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the tube (mm)</td>
<td>400</td>
</tr>
<tr>
<td>Fixing length (mm)</td>
<td>20</td>
</tr>
<tr>
<td>Average radius (mm)</td>
<td>60.565</td>
</tr>
<tr>
<td>Tube thickness (mm)</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Input parameters of the APDL analyses, which are entered by using GUI, are as follows:

Geometry of the Tube (diameter, length and thickness)

Number of Layers

Angle Orientations for each Layer

Fixing length, where end loads will be applied (for combined loading model)

9 Elastic Constants

9 Strain Strength Constants

9 Stress Strength Constants

3 Coupling Coefficients

Loading (Inner and outer pressure, Transverse Load, Axial Load and Torque)

![Figure 4.3: Stack of Layers with different orientation of fibres](image)
Analyses are done with the following order of operations:
Geometrical Properties are entered
Elastic Constants are entered
Strength Constants are entered
Loading Conditions are entered
Layer Orientation and mesh density are entered
Analysis is defined as a structural analysis
Element type is specified
Layer orientation and thickness are specified
Geometry is constructed with specified properties
Fixing areas are specified
Meshing is constructed
Boundary conditions are applied
Solution is done
Post processing is done

**Model Verification And Analysis Parameters**

There are two points, which need to be verified before performing a finite element analysis: ‘process’ and ‘inputs of the process’. The process is the APDL code, the FEA model and FEA Code. Inputs of the process are however elastic constants and strength constants, which are used as input data. After completely clarifying these two points, further analyses can be performed successfully.

Verification of both is done, by performing analyses similar to the experiments performed in literature [37]. FEA results are very close to test results, although there is some scattering involved in experimental results. It is important to note that, the composite structure in FEA are observed to be slightly stiffer than the ones in experiments.

The elastic constants for various composite materials can be taken from [3], [7], [8], [10], [19], [20], [26], and [37]-[40]. E-Glass/Epoxy (Eg/Ep) are preferred in the analyses, due to more reliable data present for these items and their dissimilar degree of orthotropy. Aramid/Epoxy (A/Ep) is rarely used in order to investigate the effect of level of orthotropy.

Another parameter to be determined is the number of integration points for a shell element. As mentioned before, a higher number of layers require a higher number of integration points. In order to examine this effect, a number of analyses are performed. By default, the written APDL codes had three integration points per shell element. Failure indices for an axially loaded C/Ep tube with constant thickness remain constant up to a certain number of layers. Beyond this value, the number of integration points is not sufficient for the number of layers modeled. Some error occurs and the failure index
starts to increase. Similar results can be obtained for stress or strain values, which are obtained from the same analysis (Fig. 4.4).

**Figure 4.4** Variation of Failure criteria by Number of Layers

**Figure 4.5** Variation of Hoop Stress/Inner Pressure by Number of Layers, for an axially loaded C/Ep tube with constant thickness

**Figure 4.6** – Variation of failure indices by winding angle for a C/Ep tube, which is loaded by pure internal pressure
5. CONCLUSIONS

Effect of boundary conditions has been evaluated which is essentially interesting for numerical modeling. An optimal angle of ±55° is proposed, which allow us to obtain a stress field which approaches asymptotically to the reference case.

Optimal layers of six are preferred to get optimal properties of Glass fibre epoxy composites.

The stresses inside the transition zone do not depend significantly on the size of the elements but mainly on the characters of anisotropy. The size of the transition zone is limited to about two elements.

During test modeling the same effects were observed in the transition zone, so the problem was considered as three dimensional.

Measured ad predicted through thickness material properties and the process induced residual strains of thick wound tubes. The measured youngs Moduli for ±55° winding angle were well predicted. Even though the variation in youngs Moduli was small over the winding angle.

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