International Journal of Mechanical Engineering and Technology (IJMET)
Volume 10, Issue 05, May 2019, pp. 450-464, Article ID: IJMET_10_05_046
Available online at http://iaeme.com/Home/issue/IJMET?Volume=10&Issue=5
ISSN Print: 0976-6340 and ISSN Online: 0976-6359
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ANALYSIS AND EXPERIMENTAL VALIDATION OF COMPOSITE LAP JOINT WITH CRACK FOR AEROSPACE APPLICATIONS

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ABSTRACT

Composite materials have made way to several different fields, including aerospace structures, under water vehicles, automobiles and robot systems etc. Due to the high strength they are widely used in the low weight constructions and also used as a suitable alternative to metals. ANSYS FEA tool has been used for stress distribution characteristics of single lap joint with crack in-built in adhesive layer. In several different applications and also for joining various composite parts together, by using epoxy adhesives. Modeling and static analysis of 3D Models of lap joints were carried out and compared for two different composite materials. The present study deals with the analysis of single lap joint subjected to tensile load and the stress distribution in the joint members under various design conditions are to be found.

The fracture characteristics of single-lap bonded joints in composites to be investigated by structural analysis and experimentally. The effects of bonding method, surface roughness, bond line thickness and the existence of fillet on the failure characteristics and strength of bonded single-lap joints were evaluated experimentally. The failure process, failure mode and the behavior of load-displacement curve was apparently different according to bonding method to be evaluated.

Key words: Composite Lap joint, adhesive layer, fracture characteristics, Adhesive joint Analysis etc

Cite this Article: CH V K N S N Moorthy, Paidi Raghavulu, Vankayala Jagadeshwar Babu, Ayyagari Kiran Kumar, Dhanekula, V Srinivas, K Ramaswamy, Analysis and Experimental Validation of Composite Lap Joint with Crack for Aerospace Applications, *International Journal of Mechanical Engineering and Technology* 10(5), 2019, pp. 450-464.
http://iaeme.com/Home/issue/IJMET?Volume=10&Issue=5

1. INTRODUCTION

A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level and are not soluble in each other. Most commonly, composite materials have a bulk phase, which is continuous, called the matrix, and one dispersed, non-continuous, phase called the reinforcement. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers, etc. The example of composite material is given in Fig.1.

Figure 1 Composite Material

1.1. Classification of Composites

Composites are classified based on:

- Geometry of the reinforcement
- Type of matrix

Based on the geometry of the reinforcement composites are classified into Particulate, Flake and Fibers.

Based on the type of matrix —

1. Polymer matrix
2. Metal matrix
3. Ceramic matrix

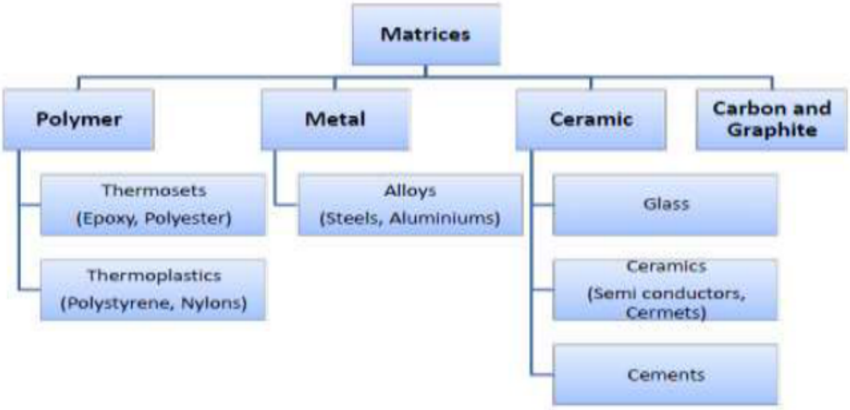

Figure 2 Classification of composites

1.2. Types of Composite Joints

There are two types of joints in FRP composites: - Adhesive joints (Permanent Joint) and Mechanical joints (Temporary Joint). These two types of joining are generally independent from each other but some time combined in a product to get additional benefit. Adhesive bonding is the most common type of joint used in composites joining. In adhesive bonding, two substrate materials are joined by an adhesive. In mechanical joints, rivets bolts, and/or screws are used to form the joint.

Adhesive Joints

The adhesive joint is made between two substrate (Adherends) material with the help of an adhesive (e.g., epoxy, methyl acrylate cyanoacrylates, anaerobics, silicones, or phenolics). From the large variety of adhesives, the optimum selection of the adhesive material is very important. The selection of the adhesive material depends upon type of composites, applications, the service environment and the most importantly the cost. The adhesive materials are classified as: structural, pressure sensitive, hot melt, water based and radiation cured. Structural adhesives are the most commonly used when joining of fiber reinforced composites is required. Various types of adhesive joints (Fig. 3) are made with the help of adhesive bonding, for example, single lap, tapered lap, scarf, butt, strap, double strap, tapered double strap, double lap and stepped lap.[6-9]

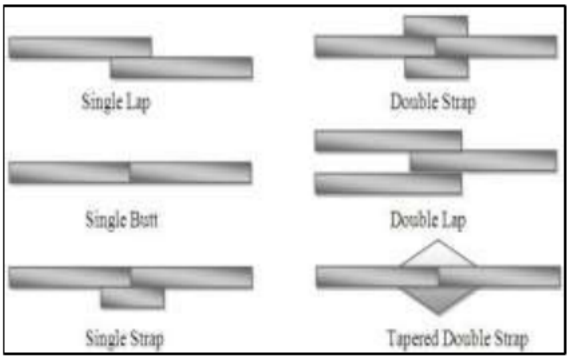

Figure 3 Types of Adhesive Joints

Mechanical Joints

Mechanical joints are made in fiber reinforced plastics composites by drilling a hole and placing a mechanical fastener between two joining members. Examples for mechanical joints are bolting, riveting, screw and pin joints. For most of the mechanical joints, an overlap is required in two mating members. The mechanical joints can be a single lap joint, double lap joint or butt joint.

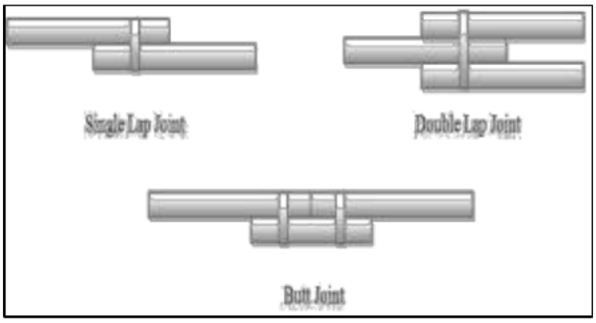

Figure 4 Various types of Mechanical Joints

1.3. Types of failures for a laminate

A laminate will fail while increasing the thermal and mechanical loads, however, may not be catastrophic.Failure modes are determined by the quality of the bond at each interface, specimen geometry and loading. They must be characterized to gain a full understandingof the properties of the adhesive and thejoint being investigated. Fig.5 (MD Banea and LFMda Silva, 2008).[1-5 &10]. It is possible that somelayer fails first and that the composite continues to take more loads until allthe plies fail. Failed plies may still contribute to the stiffness and strength ofthe laminate.

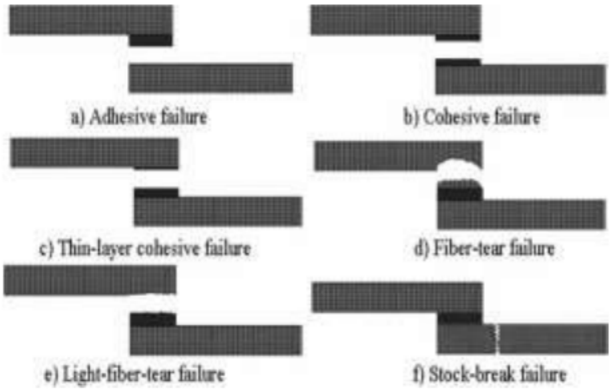

Figure 5 Types of Failure modes of Laminate

2. DESIGN OF COMPOSITE LAP JOINT

Joining of fiber reinforced composites (FRPs) leads to a new dimension of concern among the researcher. The joining becomes an imperative and necessary domain to join individually processed composite parts into a usable assembly. Joining of FRP composites seems to be simple but it is much more than that. The design of joint in FRP composites is a very critical issue. The joint is a source of stress concentration and improper design may lead to increase in stress concentration and may become a cause of failure during in service of the product. Joint add manufacturing depending time and labor cost to the product. Different joining methods can be used upon the complexity of the structure or product and its application area considering. Fig.6. [11-15].

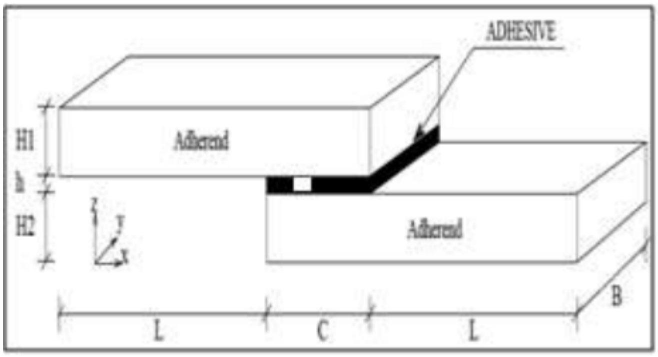

Figure 6 Design of composite lap joint with inbuilt crack

The following conditions should satisfy Design of a joint

1. Allowable shear stress and tensile stress of adhesive should not exceeded
2. Allowable in-plane shear stress and through-thickness tensile stress of adherend should not exceeded

For maximising the static strength and fatigue performance of adhesively bonded joints include (NPL Manual, 2007), [46-52]

- Minimise shear and peel stress concentrations - shear and peel stress concentrations present at bondline ends can be minimized by using the tapered or bevelled external scarf or radiused adhesive fillets. Significant increases in the joint strength compared with square-ended bondlines can be achieved
- Increasing either the adherend stiffness or adherend thickness results in an increase in load-carrying capacity of the single-lap joint. The use of stiff or thick adherends will reduce peak stress levels and which promotes more uniform adhesive stress distribution. By using the absolutely rigid adherend will not prevent the formation of stress concentration at the ends. The overlap length must be long to ensure that the shear stress in the middle of the overlap is low to avoid creep. Short overlaps result in failure through creep-rupture. In order to have a uniform shear stress distribution the overlap length must be 10 times of adhesive thickness.[16]
- the joint must be loaded in the direction of maximum strength of the adherend. The bonded joint needs not only to be loaded in the direction of maximum strength, but also loads in the weak directions need to be minimised.
- Bond must have a uniform thickness and it is recommended to join identical adherends to minimise skewing of the peak and normal stresses, and to reduce thermal residual stresses due to differences in coefficient of thermal expansion values.[17].
- interlaminar shear or tensile failures of composite adherends is avoided. Also, ensure the laminated adherend must be symmetric, which ensures the coupling stiffness components of the laminate are zero (i.e. no twisting).[18-21].
- Account for differences in thermal expansion coefficients of the adhesive and adherends. This Difference can lead to bending stresses and residual stresses, which will decrease the joint performance.

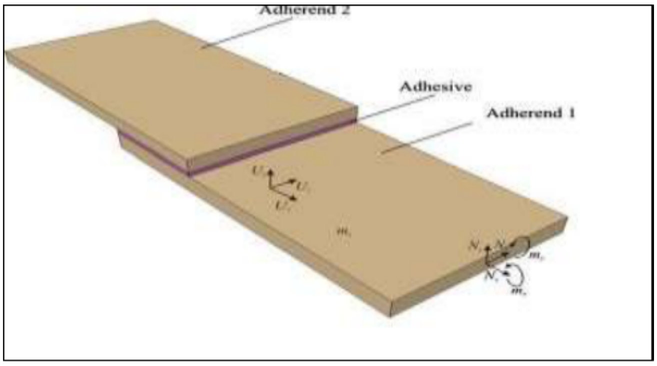

Figure 7 Configuration of composite Lap Joint

2.1. Material Selection

Carbon fibers have high strengths and low densities and so are used in many applications, particularly aerospace, in spite of their higher cost. Fiber reinforced plastic composites are superior to metals in terms of specific strength and stiffness, corrosion resistance, and formability. Composite materials, therefore, are used for primary structures of small or mid-sized nautical vessels, and aerospace structures.

Adhered Specifications:-

Young’s Modulus

Ex = 1.17E +005

Ey = 8000
Ez = 8000
Poisson Ratio
PRXY = 0.25
PRYZ = 0.32
PRXZ = 0.25
Rigidity Modulus
GXY = 3850
GYZ = 4500
GXZ = 3850

Adhesive properties:-

Most of the industries are demanding new adhesive materials with advanced properties which should satisfy the required conditions for a specific application. In order to meet the necessary requirements, new adhesive materials are developed with more advanced properties. Although, there are numerous adhesive materials available in the market, selection of adhesive materials for a specific application is not an easy task as it depends on many factors (i.e. adherend type to be bonded, curing temperature, expected environmental condition during service, type of load, cost etc.).[22-27] Nowadays, the extensive application of adhesive bonding in the industry is a positive step, but reuse, recycling and recovery of bonded parts are the major concerns mainly because of environmental issues. To overcome this, the adhesive bonding should easily dis-bond without damaging the structure.

- Araldite AW-106
- Hardener – HV953U

Adhesive Specifications:-

Ex = 5
PRXY = 0.25 (For Orthotropic materials)

2.2. Design of Composite Adhered:

Considered the carbon epoxy composite plate for adhered and ply sequence is given, and configuration is given [30]

S.No	Layer type	Orientation (°)	Thickness (mm)
1	Hoop	0	0.40
2	Helical	45	0.40
3	Helical	45	0.40
4	Hoop	0	0.40

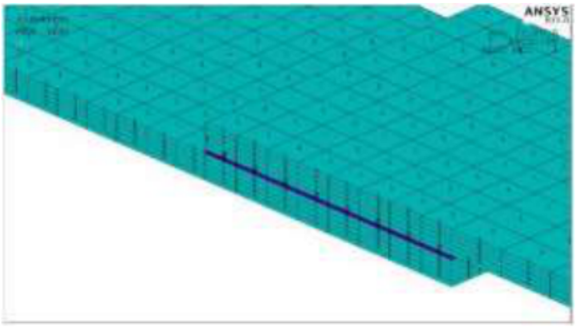

Figure 8 Ply Sequence of composite Adhered

2.3. Stress Calculations for Composite Lap Joint

The ply design and the stresses, loads calculations are carried out based on the classical laminate theory (CLT). [34] The details of CLT [2] as follows:

Properties for Carbon fiber T-700:

E1 = 117GPa; E2 = 8GPa; ν = 0.3.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \qquad (1)$$

Step-1: Calculate the stiffness matrix based on the engineering constants:

$$Q = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \qquad (2)$$

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j}$$

$$Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}} \quad Q_{12} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} \quad Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}} \quad Q_{66} = G_{12} \;\; Q_{12} = Q_{21} \qquad (3)$$

Stresses are within the strength of composite materials and CE plates are safe during testing of lap joint. The fiber orientation 30° and 45° are very close in transverse tensile stress and manufacturing point of view, 45° fiber is selected along with 0° fiber orientation.

2.4.FEA Elements

- Define element type to Quadrants and nodes.
- Create key points to form areas of rectangles.
- Define material properties for each area Glue the areas together to represent adhesion.
- Create mesh with a minimum of 10 elements.
- Define loads and fixed points.
- Generate solution and contour plots.

The numbers of FEA elements are used for analysis of joint. The finite element mesh is generated using a three-dimensional brick element 'SOLID45'. (ANSYS R15.0).[28 & 29] This element is a structural solid element designed based on three-dimensional elasticity theory and is used to model thick orthotropic solids. The element is defined by 8 nodes having three degrees of freedom per node: translations in the nodal x, y, and z direct.

The $U_x = 0$,$U_y=0$ and $U_z=0$

Figure 9 Loads and Boundary Conditions

The boundary conditions applied in this composite plate is one end is fixed and other end the load is applied as shown in fig.9.

[30-33] FEA analysis of adhesive joint gives some important observations which are given as below:

- In this type of joint The highest stress concentrations occurs (at the free ends of the joint).
- The centre of the joint transfer less loads.
- Tapered or bevelled external scarf or radiused adhesive fillets minimize the stress concentrations at the free ends of the joint.

Standard test method for Strength Properties of adhesives in Shear by Tension Loading of single Lap Joint Laminated Assemblies (As per ASTM Standards D3165)

This test method (Note-1) is intended for determining the comparative shear strengths of adhesives in large area joints when tested on a standard single-lap-joint specimen and under specified conditions of preparation and testing. Adhesives respond differently in small versus large area joints.

The test method is useful in that the joint configuration closely simulates the actual joint configuration of many bonded assemblies. Surface preparation of the adherends can affect the apparent shear strength of the adhesive and can be oe of the variables under study. [35–38] This test method is also useful as an in-process quality control test for laminated assemblies. Either in practice, the laminated assembly is made over size and test specimens removed from it or a percentage of the assemblies are destructively tested.

The misuse of strength values obtained from this test method as design allowable stress values for structural joints could lead to product failure. Property damage and human injury. The apparent shear strength of an adhesive obtained from a given small single-lap specimen may differ from that obtained from a joint made with different adherends or by a different bonding process. The norm variation of temperature and moisture in the service environment causes the adherends and the adhesive to swell and shrink. The adherends and adhesive are likely to have different thermal and moisture coefficients of expansion.

Even in small specimens, short -term environmental changes can induce internal stresses or chemical changes in the adhesive that permanently affect the apparent strength and other mechanical properties of the adhesive. The problem of predicting joint behavior in a changing environment is even more difficult if a different type of adherend is used in a larger structural joint than was used in the small specimen.

The apparent shear strength measured with a single-lap specimen is not suitable for determinate design allowable stresses for designing structural joints that differ in any manner from the joints tested without thorough analysis and under- standing of the joint and adhesive behaviors.

Single-la tests may be used for com paring and selecting adhesives or bonding processes for susceptibility to fatigue and environmental changes, but such comparisons must be made with great caution since different adhesives may respond differently in different joints . Review Guide D4896 for further discussion of concepts for interpretation of adhesive-bonded single- lap joint data.

3. PREPARATION OF TEST SPECIMENS

For initial preparation, trim the joint area in accordance with dimensions. Cut test specimens as per required dimensions. Carry out the cutting operation to avoid over-heating or mechanical damage to the joints. Measure the width of the specimen and the length of the overlap to the nearest 0.01 in. (0.25 mm) to determine the shear area.

In a filament winding process, a band of continuous resin impregnated rovings or monofilaments is wrapped around a rotating mandrel and then cured either at room temperature or in an oven to produce the final product.[39]

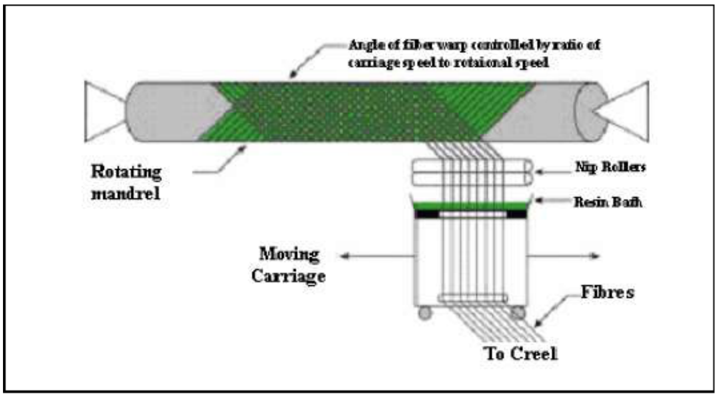

Figure 10 Layout Filament Winding Process

The mandrel can be cylindrical, round or any shape that does not have re-entrant curvature. Modern winding machines are numerically controlled with higher degrees freedom or laying exact number of layers of reinforcement.

After Filament winding, the laminate is cured in an oven having accurate temperature control. The flat mandrel is placed inside the oven on metal stands. The following cure cycle was followed [40-43]

- Raise temperature of the oven from room temperature to 120°c in 30minutes with heating rate of 2 to 4°c per minute
- Hold the temperature at 120°c ±5°c for 2 hours
- Raise temperature of the oven from 120°c to 150°c in 30 minutes with heating rate of 2 to 4°c per minute
- Hold the temperature at 150°c ±5°c for 4 hours
- Switch off the oven and allow the component to cool naturally.
- Open the door and remove mandrel when it is below 40°c.

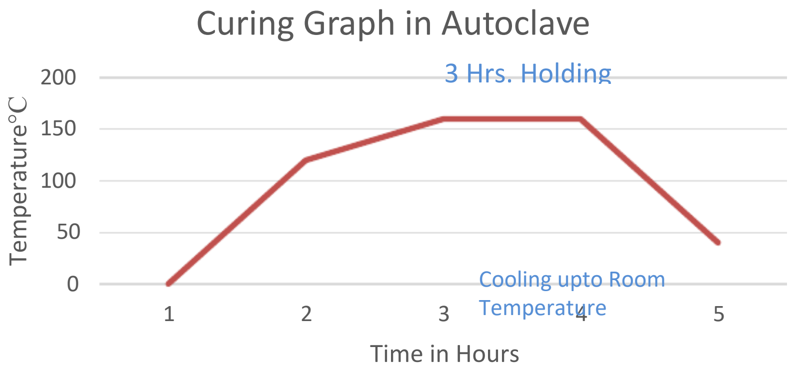

Figure 11 Curing graph in Autoclave.

Now bonding of the test specimens is done by an adhesive layer. The adhesive layer is a combination of both Araldite AW-106 and Hardener HV953U. The ratio of this will be 1:1. Allow some time to bond the test specimens that may be a day and become hard. For the inbuilt crack bond test specimens the release fabric is kept between the specimens to generate a gap. After the adhesive become hard the release fabric is taken out and the gap is generated in fig.11.

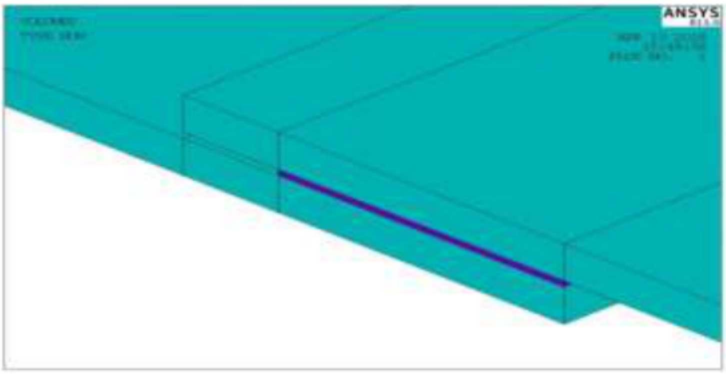

Figure 11 The inbuilt crack is generated using the release fabric

3.1. Testing method and Equipment Structure

The machine, load cells and extension meter are to be calibrated annually in accordance with international standards. Main parts of UTM are Load frame and its controls, Tower assembly, Digital control Panel and Computer. Preventive maintenance like greasing the moving parts, cleaning the filters and other preventive maintenance should be carried for better performance of the instrument. UTM set up given in Fig 12.

The detailed Specifications are:

- Load range: 10 N - 50 KN
- (Accuracy being 1 N)
- Stroke : 1.0 m
- Provision for extensometer should be available.

Figure 12 Universal Testing Machine (INSTRON)

Pin the specimens or if jaws are used, place in the grips of the testing machine so that the outer 25.4 mm (1inch.) of each end are in contact with the jaws and so that the long axis of the test specimen shall coincide with the direction of applied pull through the centerline of the grip assembly. Apply the loading immediately to the specimen and will get the results and graphs.[44-45]

Types of Loads that applied to the specimens:-

My cylinder has an original length of I_o and surface area of A_o. As I pull on my material with the force F the cylinder will lengthen and the resulting length will be l. Stress, σ, is defined as the force divided by the initial surface area, $\sigma=F/A_o$. This pulling stress is called tensile stress. If instead of pulling on our material, we push or compress our cylinder we are introducing compressive stress. If instead of applying a force perpendicular to the surface, we apply parallel but opposite forces on the two surfaces we are applying a shear stress. Stress related to shear is torsion stress. If we hold one end of our cylinder fixed and twist the other end as shown in the figure below Fig.13

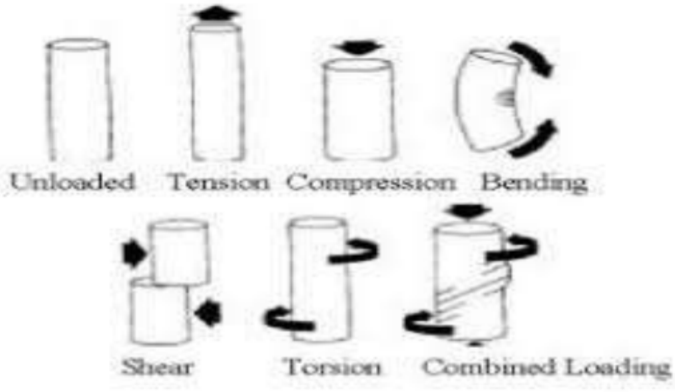

Figure 13 Types of load testing.

Shear stress is the amount of force per unit area perpendicular to the axle of the member. When you stepped on the wooden stick really hard, the impact load on the stick caused two types of stresses:

- Bending stress, also called flexural stress, is parallel to the axle of the member.
- Shear stress is perpendicular to the axle of the member.

4. CONCLUSION

This study presented single lap adhesively bonded joint configurations that are employed in various applications. The main outcomes of this study are to understand joining of two composite plates using adhesive joint. In several different applications and also for joining various composite parts together, by using epoxy adhesives. Modeling and static analysis of 3D Models of lap joints were carried out and compared for two different composite materials. The present study deals with the analysis of single lap joint subjected to tensile load and the stress distribution in the joint members under various design conditions are to be found.

The overlap length is most important factor which affects adhesive strength, adhesive properties, adherend properties and joining procedure also. For the optimal overlap length the joint strength is maximum with minimum applied adhesive which increases load bearing capacity of joint. Elastic and plastic behavior of adherend is very important for obtaining maximum joint strength. In order to use adhesive Joint for bonding purpose it is necessary to know the mechanical and chemical properties of adhesive. The tensile strength of structural adhesive is obtained by loading the bonded adhesive plates on UTM to fail against the tensile mode. The most of problems in numerical analysis are addressed to mechanical properties of adhesive which are often publicly unknown. Accuracy of adhesive properties is influenced with reliability of materials models. Parametric study on lap joints in FEA gives stress peaks at critical locations by a more refined FE mesh.

The fracture characteristics of single-lap bonded joints in composites to be investigated by structural analysis and experimentally. The effects of bonding method, surface roughness, bondline thickness and the existence of fillet on the failure characteristics and strength of bonded single-lap joints were evaluated experimentally. The failure process, failure mode and the behavior of load-displacement curve was apparently different according to bonding method. Investigation found that the decrease the effective bonding length leads to reduce the load bearing capability. In future, adhesive crack propagation can be worked out using VCCT technique.

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